THEORETICAL PEST MANAGEMENT DECISIONS BASED ON QUANTITATIVE ANALYSES OF POPULATION ECOLOGY, BIOLOGY, AND BIODYNAMICS OF *TETRANYCHUS URTICAE* KOCH AND ITS PREDATOR, *PHYTOSEIULUS MACROPILIS* (BANKS)

By

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A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1976

ACKNOWLEDGMENTS

I express my sincere gratitude to Dr. Harvey L. Cromroy (Chairman of the committee), Dr. Sidney L. Poe (Cochairman of the committee), Dr. Reece I. Sailer, Dr. James L. Nation, and Dr. John A. Cornell for advice and criticism of the dissertation. I also thank Dr. Will E. Waters, Director, and Ms. Amegda J. Overman at the Agricultural Research and Education Center, Bradenton, Florida for their help and use of the facilities at the center.

Special appreciation is extended to my wife for her assistance in typing the manuscripts and the final copy and to Mr. T. H. ing for his criticism of the first draft of the manuscript. Thanks are also due to Dept. of Entomology and Nematology for financial support which made this study possible.

A very special gratitude is extended to my parents, who provided encouragement and understanding.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table		Page

LIST OF ILLUSTRATIONS

Figure		Page

Abstract of Dissertation Presented to the Graduate Council
of the University of Florida in Partial Fulfillment of the Requirements
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December, 1976

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Population biology, ecology and dynamics of the twospotted spider mite, *Tetranychus urticae* Koch, and its predator, *Phytoseiulus macropilis* (Banks), on strawberries, were studied and their responses to acaricides, plant sources, acaricides, and ammonium nitrate levels were established.

Three experiments of either factorial or completely randomized block design were used to collect data on basic biology, predation potential, and ecological interactions useful for pest management. The methodology used in this study included correlation coefficients and partial correlation coefficients, regression models, and mathematical spiral of Archimedes. In addition, relatively well-developed mathematical theories, such as Cesicelaw and differential equations were used. The analyses were designed to show how quantitative mathematical models could be used to model the biodynamic system involving the predator-prey-host plant for the purpose

of developing a practical pest management program.

Satisfactory control of the spider mite population and a good plant condition as defined by plant leaf count were achieved from predator release at a 1:16 ratio. The functional and dynamic responses of spider mites as well as their predator populations suggested that timing of acaricides should be applied at two-week intervals. Data also showed that *P. macropilis* was a promising alternative control measure to chemical control.

'Pest load capacity' and 'tolerance capacity' of strawberry plants to the twospotted spider mite population density were studied. A 'pest load capacity' was determined to be 21 to 30 mites per leaf and 'tolerance capacity' to be 5 to 6 mites per leaf from four regression lines.

Population densities of ten generations of twospotted spider mite and its predator, *P. macropilis*, were used to estimate the best initial predator-prey ratio (1:128). This ratio (1:128) was the only one which appeared to reach the equilibrium point among the tested ratios.

Development of resistance of twospotted spider mite to naled and dicofol were measured in the laboratory and in the field. Dicofol 1.6 EC applied at 1 lb ai/acre is the best acaricide among the tested chemicals. Among all the two-chemical or three-chemical combinations, the combination of dicofol (1.6 EC, 0.5 lb ai/acre) and naled (8 EC, 0.5 lb ai/acre) was the only one which did not show any antagonistic effect.

The best pest management strategy which integrated biocontrol with soil treatment, fertilizer and plant source indicated that the greatest potential lay with a California-produced plant grown in soil treated with CGA-12223, with increased ammonium nitrate (four lbs per plot) fertilizer

and an initial release of predator at a ratio of one predator to sixteen prey. However, from the hypothetical regression model, the optimal plant condition can also be maintained by release of the predator at a predator to prey ratio from 1:8 to 1:6 at introduction. Predators being released at higher or lower initial predator-prey ratios did not result in better plant condition.

CHAPTER I
INTRODUCTION

The objective of pest management is the protection of crops through the application of technology designed to optimize economic return without hazard to human health and with minimal adverse effect on the environment. Several possibilities exist for the management of spider mite populations. Plant resistant varieties that have been developed through breeding (Shanks and Barritt, 1975), biological control agents (McMurtry et al., 1970, Pruszynski, 1973, Swenson, 1973), cultural practices and genetic manipulation (McEnroe, 1970. Ong and Dalfmatyne, 1974, Overmeer 1973), and chemical applications or integration of these tactics have all been used. The management of twospotted spider mite population depends upon and is facilitated by (1) adequate knowledge of the mite's biology, life history, and host-plant relationship, (2) sufficient data on the population dynamics of the spider mite and its natural enemies as well as the interactions between predator and prey, (3) judicious use of chemical acaricides, (4) timing of pest management tactics.

Experiments were designed to collect data on the basic biology and ecology required for pest management. The methodology used consisted of basic statistical analysis, such as the fitting of regression models, and some relatively well-developed theories of control engineering described by differential equations or derivatives thereof. The experiments and data analyses were designed to show quantitatively how mathe-

matical modeling of biodynamic systems of predator-prey-host plant relation or multiorganismic systems is feasible in ecological and practical pest management terms

The objectives of this research and organization of results are indicated by the following chapter headings (1) Chapter 2 describes the materials and experimental designs used in this research, (2) Chapter 3 shows by quantitative and numerical approaches the significance of the initial ratio of predator-prey predation as well as other factors which affect the host plant, pest and its predator population, (3) Chapter 4 deals with polynomial regression models fitted by both weighted and unweighted least squares for the purpose of estimating the best release ratio of predator to its prey, (4) Chapter 5 interprets the pest load capacity and tolerance capacity of strawberry plants under experimental conditions (5) In Chapter 6 the nearness of the estimation of predator-prey ratio to the ecological equilibrium line is measured by the value of R-square of linear and/or curvilinear regression lines

Selection of chemicals and methods for pest control are discussed in Chapters 7 and 8. Since resistance of spider mite population to acaricides has been frequently reported (Abo-El-Ghar, 1972, Abo-El-Ghar and Boudreaux, 1958, Cranham 1974, Hansen, 1958, Helle, 1963, McEnroe and Lokecy, 1969, Ong and Ballantyne, 1974), toxicological tests of the level of resistance in the twospotted spider mites to omited and dicofol are discussed in Chapter 7 In Chapter 8, a field experiment is employed to evaluate the chemicals, omited, dicofol, Omite®, Vendex® and their mixtures for their impact on the mite population The synergistic and

antagonistic effects from using two and three chemicals in combination are discussed and evaluated.

CHAPTER 2
EXPERIMENTS

Experiment 1

Experiment 1A

The commercial strawberry variety 'Tioga' plants from nurseries in California and North Carolina were set at the University of Florida Agricultural Research and Education Center at Bradenton, Florida, during mid October 1973, through plastic mulch on raised beds of Leon fine sand. Fertilizer, 18-0-25, at the rate of 1,000 lbs per acre and two rates of NH_4NO_3 (2 lbs per plot and 4 lbs per plot) were added atop the middle of a 3' x 9' bed prior to mulching. Chemical classes of nematicides were: Organic phosphates: Ethoprop (O-ethyl S, S-dipropylphorodithioate), and CGA-12223 (O- (5-Chloro-1-(1-methyl)-1H-1, 2, 4, -triazol-3-yl) O, O-diethyl phosphorothioate), Carbamate: Carbofuran (2, 3 -dihydro-2, 2-dimethyl-7 benzofurany methylcarbamate), which were also broadcast on bed surface prior to mulching at concentration of 10 lbs ai per 100 gallons, 4 lbs ai per 100 gallons, and 10 lbs ai per 100 gallons respectively. Plots of 6 plants were set in double rows of 3 plants each on 12-in. center and 3 plots were set on the same bed (Figure 1a). The plots making up the treatment combinations with six healthy robust plants with a high number of leaves, individually counted, were surrounded by a 1-in. wide tanglefoot barrier on the plastic mulch. The number of spider mites per plant was determined by counting. The adults of the

predator, *Phytoseiulus macropilis* (Banks), were released singularly with a fine camel brush onto each plant in sufficient number to establish the designed ratio of predator-prey. The experimental design was set out in a completely randomized block design arrangement. Two replicates of the California source and at the high ammonium nitrate level made up two of the four blocks. The remaining two blocks contained the North Carolina source at the low ammonium nitrate level (Figure 1a). CGA-12223 was applied to the plots containing the North Carolina plant source. Ethoprop was applied to one of the blocks containing the California source while carbofuran was applied to the other plots containing the California plant source. Check, no nematicides applied, was assigned to the North Carolina source.

Predators for release were obtained from a twospotted spider mite population colonized on potted lima bean plants, var. 'Henderson' (Shih et al., 1976a, 1976b). The first release of predator mites was made on January 17, 1974 and the number of mites per leaf including both prey and predator were monitored weekly through March 21, 1974. Observations and assessments of mite population were made under a 10x magnification on the plant leaves to avoid manual defoliation effects.

Experiment 1b

Each of the 4, 6-strawberry plant plots which are not treated with any nematicides, has an ammonium nitrate level either high or low. Fertilizer, 18-0-25, at the rate of 1,000 lbs per acre and 2 lbs or 4 lbs per plot of NH_4NO_3 were added atop the middle of 3' x 9' bed prior to mulching. The design arrangement containing four blocks follows a two-way classifi-

cation scheme utilizing strawberry source and ammonium nitrate level (Figure 1b). Two blocks, one with high ammonium nitrate and one with low ammonium nitrate, were planted with strawberry plants of the California source. The other two blocks contained strawberry plants of the North Carolina source with a low ammonium nitrate level and strawberry plants of the Florida source with a high ammonium nitrate level. The mechanism of applying fertilizers and planting and sampling of strawberry are the same as described in Experiment IA. Unlike the blocks in Experiment IA, which consisted of only six plots, the blocks in this experiment contained eighteen plots.

Data from both experiments were analyzed using analysis of variance techniques and the significantly different means were determined by Duncan's multiple range test and Dunnett's test. Probability of relationships, over a period of four weeks, between population densities of predator and prey, or predator in the past and present, or prey in the past and present, and between population densities of prey and host plant condition (number of leaves per plant) were established by correlation coefficients. Based upon the spider mite population level and host plant condition, two regression models were fitted by both weighted and unweighted least squares methods. The best release ratio was obtained from the regression equations.

The weighted least squares method is used for a regression analysis when the observations are correlated and/or when the variances of the observations are not all equal. The ordinary (unweighted) least squares estimation formulae are not valid in these cases. If one wishes to use

the unweighted least squares systems, the original observations have to be transformed to other variables which are uncorrelated and have equal variances (Drapper and Smith, 1968). Coefficients of correlation and partial correlation were used to establish two regression models which would estimate the 'pest load capacity' and 'tolerance capacity' levels of the host plant to the phytophagous mite load. Seasonal density and fluctuations of predator and prey populations were used to determine which predator-prey release ratio was most likely to reach an ecological equilibrium point at the time the plant approached its maximum pest carrying capacity.

The techniques used and the resulting regression models fitted were the efforts made in order to reach the following objectives: (1) to estimate the best release ratio based on plant condition, which is discussed in Chapter 4; (2) to estimate 'pest load capacity' and 'tolerance capacity' of strawberry plant, which are discussed in Chapter 5, and (3) to establish ecological equilibrium, which is discussed in Chapter 6.

Experiment 2

Two blocks of commercial strawberries of 'Tioga' variety were planted at the University of Florida Agricultural and Research Education Center at Bradenton, Florida, during mid October of 1973. Each block consists of sixteen beds with three 3' x 9' plots in each bed in a plot arrangement similar to the illustration in Figure 1b. Fertilizer, 18-0-25, at a rate of 1,000 lbs per acre, was added atop the middle of each bed prior to mulching. Two rows of nine plants each were set on 12" center through plastic polyethylene mulch on a raised bed of Leon sand. The

two blocks were sprayed weekly with naled and dicofol, respectively, from January 15 to March 18, 1974. A LC_{50} test with each of the toxicants was conducted in the laboratory before each weekly spraying. Within twenty-four hours after the LC_{50} test of each week, the acaricides were applied with a hand sprayer at a dosage equivalent to 100 gal water per acre and at a concentration equivalent to LC_{50} of the last testing. The LC_{50} test was conducted in the following manner. Young females, eclosed within twenty-four hours, were collected with a lima bean leaf from each plot. The leaves were kept fresh in plastic water-tubes (manufactured by Syndicate Sales, Inc., Kokomo, Indiana). Fifty young females from the same block were mounted on a piece of double-faced tape, stuck on a microslide, under a 10 x dissecting scope with a NO. 00 camel hair brush. The mites were mounted alive and venter-up in five rows of ten each. The slides with mites were kept on a slide holder and placed in a desiccator in which was kept a tray of water and a RH of 95-100% was maintained. The acaricides, naled and dicofol, were dissolved in acetone to make a weighted/volume stock solution. They were further diluted with a solvent of 1:1 acetone : water mixture into desired concentrations (Saba, 1971). When all the required number of slides with mites were prepared, the slides of mites from each block were individually dipped in their respective toxicants of various concentrations for two seconds. The treated slides with mites were also kept in a desiccator with 55-100% Relative Humidity. The entire LC_{50} test was conducted at a temperature of $27 \pm 2^{\circ}C$. Mortality was counted under a 10 x magnification twenty-four hours after dipping. If a mite was lightly stroked with a camel hair brush and no responses of waving legs were found, it was counted as dead.

The data were analyzed for LC_{50} by using linear regression lines (Snedecar, 1966).

Experiment 3

Commercial 'Tioga' strawberries were planted in mid October, 1973 through black plastic polyethylene mulch on raised beds of Leon sand at University of Florida Agricultural Research and Education Center, Bradenton, Florida. Fertilizer (18-0-25) was applied at a rate of 1,000 lbs per acre in a center on the beds prior to mulching. The plots were arranged in double rows of ten plants each set on 12" centers in a randomized block design. Acaricides were applied weekly with a band sprayer at a dosage equivalent to 100 gallons of water per acre on January 29, February 6, 21, and March 6, 1974 to the plots.

Experiment 3A

Each plot received dicofol, naled, omite or a combination of toxicants (Table 12). In order to avoid possible incompatibility of the ingredients in a mixture, whenever possible, emulsifiable concentrates (EC) were mixed as were wettable powders (WP). Spider mite populations were sampled on January 24, 31, February 8, 22, and March 8, 1974. Ten strawberry leaves from different plants were randomly taken from each plot, and mites were brushed from the leaves with a Henderson-McBurnie machine onto a glass plate. Population counts were made under a 10 x magnification.

Experiment 3B

Two rates of organotin (Vendex®) were tested in addition to the previous chemicals (Table 13). Mite populations were determined from ten

leaves from each plot by counts made under 10 x magnification. Samples of January 29 were taken immediately before the chemical spray and were used as a correction factor. Thereafter, samples were taken on January 30, 31, February 1, 3, 4, and 6 to measure the response of spider mite population following treatment. The data were transformed to a corrected mortality of spider mite population due to the chemical by use of the modified Abbott's formulae A, B, and C (Henderson and Tilton, 1955).

If T_b is the average number of mites per leaf per plot before treatment, T_a the average number of mites per leaf per plot after treatment, C_b is the mean number of mites per leaf per 5 plots from the check plots before the treatment, C_a is the mean number of mites per leaf per 5 plots from the check plots after the treatment, X_a is the average number of mites per leaf per plot at day 5, or day 6, or day 8 after the treatment, X_b is the average number of mites per leaf per plot at day 3 after the treatment, C_{a1} is the mean number of mites per leaf per 5 plots from the check plots at day 5, day 6, or day 8 after the treatment, and C_3 is the mean number of mites per leaf per 5 plots at day 3 after the treatment, then

(A) Actual number of mites per leaf $= \dfrac{T_a \times C_b}{C_a}$.

(B) Corrected percentage mortality from the initial population

$$= \frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$$

(C) Corrected percentage recovery from the third day after treatment

$$= \frac{X_a - X_b}{X_b} \times 100 \times \frac{C_{a1}}{C_3}$$

Sample data from Experiments 3A and 3B were tested for significance through an analysis of variance and significant means were determined using both Duncan's multiple range test and Dunnett's test. Data of Experiment 3B were used to determine the synergistic or antagonistic effects of mixtures.

CHAPTER 3
POPULATION BIOLOGY OF TWOSPOTTED SPIDER MITE, TETRANYCHUS URTICAE KOCH, AND ITS PREDATOR, PHYTOSEIULUS MACROPILIS (BANKS) ON STRAWBERRY PLANT

The importance of phytoseiids as predators of plant-feeding mite species has been recognized for years. However, in-depth studies of these predators and their prey relations are limited to population dynamics with little observation on host plant reaction. Studies in Europe with Phytoseiulus persimilis Athias-Henriot (Bogdanov, 1969, Baronet, 1973, Lipa, 1973, Pruszynski, 1973, Scopes, 1973) and in the United States with Phytoseiids (Huffaker et al., 1969, McMurtry et al., 1969, Oatman and McMurtry, 1966, Oatman et al., 1968, Shih et al., 1976a, 1976b) indicate that timely releases of predacious mites would be of value in managing twospotted spider mite populations on crops of high economic value, such as strawberries, ornamentals, and vegetables. Forr and Hussey (1967) showed that the density of the predator Phytoseiulus persimilis at introduction was critical to spider mite control. The spider mite population increases at a rate of $r_m = 0.331$ (Shih et al., 1976a). Therefore the number of predators released to prey present (1 to 30) was too low by simple mathematical calculation based on the intrinsic rate of increase of the predator and prey populations. The optimal ratio of predator released to prey present should be higher than the Forr and Hussey's studies indicated.

In order to establish an effective pest management strategy using a biological control agent, a thorough understanding of the biology of

the predator and its interaction with its prey and other various management practices is essential. Effective control of spider mite by predator mites depends on predator densities at introduction, and on maintaining the correct balance between predator and prey (Burnett, 1971, Hussey et al., 1965, Farr and Hussey, 1967).

Leaf count has been used to indicate the effect of spider mite density on plant conditions. Runners or transplants of strawberry plants generally develop their crowns and leaf area before establishment or expansion of roots (White, 1927). Mann and Ball (1923) reported that the root growth of strawberry becomes most active after a growing period of shoots, leaves, and flowers. Also, following a rapid and active period of new leaf and flower formation strawberry plants reach their highest dry weight during fruiting season. Deterioration of leaves is usually caused by senescence, disease or mechanical injury. Bolton (1966) showed that deterioration of leaves by a pathogenic disease resulted in severe decrease in yield. The deterioration and loss of leaves and their susceptibility to pathogenic parasites would undoubtedly be enhanced by spider mite damage. Since spider mite damage on strawberry plants results directly in reduction of leaves and indirectly in reduction of root system, dry weight, and yield, it seems proper to compare plant condition in relation with spider mite density in number of leaves per plant.

In this chapter, the responses of spider mite population and plant condition to different predator population densities, ammonium nitrate levels, host plant sources, nematicides and their interactions are studied.

The purpose of this chapter is to determine the minimum level of predator release depending upon actual number of spider mites in the field in order to achieve an efficient and economic control of twospotted spider mites in a commercial strawberry grove. In addition, factors influencing the population level of prey such as soil nematicide treatments and sources of nursery plants, as well as the interaction between these factors and predator mites were investigated for practical use in pest management.

Materials and Methods

The materials and methods are as described in Experiment 1A and Experiment 1B in Chapter 2. Data from Experiment 1A were also plotted in a two-dimensional diagram to show the responses of host plant condition, twospotted spider mite population densities, and M. occidentalis population densities to initial predator release ratios (Figures 2,3,4, 5, and 6).

The combined effects of initial predator release ratios on twospotted spider mite population densities and plant conditions are interpreted by an effective index which is calculated as follows:

Effective Index = (Seasonal average number of leaves per plant on predator introduced plots - seasonal average number of leaves on control plots) / (weekly average number of spider mites on predator introduced plots - weekly average number of spider mites on control plots)

Results

Release Ratio Screening

The population densities of all stages of the mites and the number of leaves per plant for ten consecutive weeks are shown in Figures 2, 3, 4, and Table 1, for five predator-prey release ratios. Seasonal maximum density of twospotted spider mite population occurred where the initial release ratio was 1:32. This is about three times the population density of the control plots, where no predator is released (Table 1). The best plant condition, indicated by the maximum number of leaves per plant, was found where one predator was released for every sixteen prey. The number of leaves on these plants was about double the number on the control plot and the 1:2 release ratio plot (Table 1). A positive correlation between the ratio of predators released at introduction and the seasonal average number of predators is found in all predator release plots except the 1:16 plot (Table 1). For example, the plot with the highest ratio of predators released at introduction has the highest seasonal number of predators found. Generally, there are no significant differences on the weekly plant response to the different initial predator ratios, but there are differences when measurements are based on the seasonal cumulative effects (Appendices 2, 3, and 4).

From the observations in Experiment 1B, the seasonal average number for the egg stage is much higher than that of individuals of all active stages within the same spider mite population. The numbers of eggs and all active stages are 28.8 ± 8.1 and 9.4 ± 6.6 ($\bar{X} \pm SD$), respectively.

The number of eggs is significantly greater than the number of individuals of all active stages ($t = 3.55$, $p = 0.01$). Under the predator released condition (Experiment IA), the number of individuals in the active stages is higher than the number in the egg stage in all ratios but 1:16 (Table I). In the control plot (Experiment IB), the number of spider mite eggs is about twice that of the combined active stages, whereas in predator introduced conditions the active stages ($\bar{X} = 154.6$) are about twice as numerous as eggs ($\bar{X} = 96.9$). The plant condition on all predator release plots and the control plots declined during the first four weeks then began to improve with the fifth week (Figures 5,6)

Spider Mite Population Density Response to Initial Release Ratio and the Feedback of Host Plant Condition

The population density of spider mites responded significantly to the predator density at the introduction as did the predator population to the spider mite density (Figures 2, 3, 4, Appendices 1, 2). All spider mite populations increased at all release ratios except the 1:2 ratio, i.e. only a predator to prey density of 1:2 would eliminate the spider mite population within a week (Figures 2a, 2b, 2c). The average time required for predators to reduce the spider mite population to less than twenty to thirty individuals per leaf (Chapter 5) was about two weeks, however the 1:32 ratio required about three weeks (Figure 2). Spider mite population density in the control plot reduced rapidly and reached a population size less than twenty to thirty individuals at the second week because of the condition of the host plants (Figure 5f).

The population of spider mites on all plots was suppressed to under thirty individuals per leaf for four weeks and then the population increased at week six. The population densities at week eight dropped

under the 'post load capacity' of the strawberry plant (Chapter 5). The initial ratios of 1:2 and 1:4 were not decreased (Figures 2a, 2b, & 2c). The spider mite population-density which crashed resulted from the two weeks high density on the host plants (Figures 3a, 3b, & 3c). Although the host plants recovered within three to four weeks after the population crash, the spider mite population did not correspondingly increase (Figure 5f).

The relationships between the population density in the present week and that in past weeks are shown in Table 8. There is a positive correlation coefficient ($r = 0.17$) between population densities of spider mites of two consecutive weeks, and they are significantly correlated to each other ($P = 0.05$). Negative correlations between mite densities with a two-week difference were not significant at 5% level ($P = 0.67$). A highly significant correlation coefficient (0.22, $P = 0.01$) was found between mite density with a three-week difference, but there was very little correlation between those with a four-week difference (Table 8). These data indicate that the population density of spider mites fluctuation around a two-week cycle (Figures 2 & 5).

The plant condition was not significantly affected by the magnitude of twospotted spider mite population density as shown by the small negative correlation values (Table 8, Figure 5). The correlation coefficients between present plant condition and the population density of the spider mite of the past four weeks as well as the present week were negative. And, although the correlations were small, the magnitude of the

correlation between the present plant condition and the spider mite populations of the past four weeks appeared to increase. Starting with a correlation of $r = -0.094$ for the previous week, the correlations were $r = -0.124$, $r = -0.147$, and $r = -0.153$ for the previous second, third, and fourth weeks, respectively. Although the present spider mite population was not correlated with the predator density of the previous week, it was significantly correlated to the predator population of the present week (Table 7).

Weekly Responses of Predator Population to Prey Density

One third of the total contribution to the average correlation coefficient (36.10) was found between predator populations of two consecutive weeks. However, there was no evidence that population density of the present week was correlated to the population density beyond the second week (Table 7).

The population density of the predator most likely depended on the prey density at the present week or during the past two weeks. The tendency was determined from the correlation coefficient (Table 7). Average coefficient between present predator density corresponding to the spider mite densities of present, one, and two weeks past were 0.39 ± 0.03, 0.26 ± 0.01, and 0.14 ± 0.003 ($\bar{X} \pm S\bar{x}$), respectively. There was no evidence to suggest that a correlation existed between population densities of prey and predator with a 3- or 4-week difference.

The predator density at introduction does influence its seasonal average (Table 3, Appendix 3), but the responses were not a linear function of the predator release ratio. The highest average number of predator for the entire study period was found at a ratio of 1:64 at the

time of introduction, nevertheless there was no significant response (average seasonal number of predators) difference between predator release ratios of 1:2 and 1:64.

Predator density was directly correlated to the population density of its prey but was not significantly correlated to simultaneous host plant condition (Table 7). A negative correlation coefficient was found between the plant condition and the predator population of the past four weeks (Table 7). This was due to a predator density that was directly correlated to the density of its prey.

The density of predatory mite eggs reached a peak within one week after release and then declined during the second week (Figure 3c). The number of individuals of active stages in the highest initial predator release plots (1:2) declined when other initial predator release plots (1:4, 1:8, 1:16) were increased to their peaks within 1 or 2 weeks after introduction. The active stages with a population density of 1:32 reached their peak at the third week instead of the second week (Figure 3). The predator population at introduction showed a functional response to its initial density at introduction (Figure 3c, 5).

Effects of Nematicides and the Interaction with Predatory Mite Density at Introduction on Strawberry Plant Condition and Mite Densities

Effects of nematicides and the interaction with predator release ratios on plant condition and mite densities are shown in Tables 4 and 6. Among the nematicide treatments, the plant condition was enhanced most and the pest population decreased most by CGA-12223 10G. When compared to the check plots, the number of leaves on the CGA-12223 treated plants was about three times and roughly 1.5 times as many in

the ethoprop-applied plots. No difference was observed between the check and carbofuran plots (Table 4). The carbofuran treated plots which had about 9.7 seasonal spider mites per leaf had the highest spider mite density among the nematicide treated plots, while CGA-12223 treated plots had 3.4 seasonal average mites per leaf (Table 4). There was no direct effect of chemical on the seasonal population density of predatory mite (Table 4). The seasonal interaction between nematicides and predator release ratio and their effect on the plant condition are shown in Table 6.

Among the nematicide treatment, the best groups of plant conditions were found on plants being treated with CGA-12223 and predatory mites release at ratio of 1:8, 1:16, 1:32 and the worst groups of plant condition were found on plants that were treated with carbofuran and a ratio of 1:4 mite density; ethoprop at ratio of 1:32 mite density; and check plants, i.e. neither chemicals nor predator release plants (Table 6). Minimal spider mite densities were found in all check plots, while the greatest densities were found on plots of CGA with 1:4, CGA with 1:16, ethoprop with 1:16, and carbofuran with 1:32.

<u>Influence of Fertilizer Level, Plant Source and the Interaction with Predator Release Ratio on Strawberry Plant Condition, and on Mite Population Densities</u>

Influence of fertilizer, plant source and the interaction with predator release ratios on plant condition and mite densities are shown in Tables 2 and 5.

<u>Fertilizer level</u>. High ammonium nitrate (4 lbs per plot of NH_4NO_3 besides 1,800 lbs per acre of 18-0-25 fertilizer) resulted in a greater number of leaves per plant and in lower spider mite and higher predatory

mite densities over the season (Table 2), i.e., the higher rate of ammonium nitrate level produced the better plant condition and biological pest management was more effective on these plants.

Plant source. The 'Tioga' strawberry plants obtained from California appeared much healthier than the plants from North Carolina (Table 2). Strawberry plants from Florida were more susceptible to spider mites and had a higher population density of mites than either California or North Carolina plants (Table 2). The North Carolina strawberry plant sources supported a higher predator density than plants from California or Florida (Table 2).

The studies on the interaction of plant source and predator release ratio on the host plant condition showed that California with 1:16 ratio combination was the best treatment combination (46.0 leaves per plant) and this was followed by treatment combinations of California at 1:32 and North Carolina at 1:8 release ratio (Table 5). The interaction of plant source and release ratio on the pest population was irregular on plants from North Carolina. However, on the California plants the influence of predator release ratio on the accumulated prey density was significant (Table 5). The California with a 1:4 ratio treatment combination was the best for suppression of the spider mite population, and the California at 1:64 was the poorest (Table 5). Predator density was not affected by any treatment combination (Table 5).

Discussion and Conclusion

Although weekly measurements of the pest and predator population density and host plant condition (number of leaves per plant) did not

differ significantly, the cumulative seasonal effects made it clear that the complex interactions existing among experimental factors showed significant influence on plant conditions and predator and prey populations (Appendices 2, 3, and 4, Tables 2, 3, 4, 5, and 6). Implications from the analysis of variance are that the independent effects of the experimental variables (predator release ratios, ammonium nitrate levels, sources of the strawberry plants, and nematicide treatments) are different for each combination of variables, and hence, must be studied independently.

Independent Effects of Experimental Variables

Effect of initial predator release ratio. The mathematical expression which best describes indirect response of plant condition due to the initial predator release ratio takes the form of a quadratic function, i.e., the ratio of 1:16 was the best, followed by 1:8, 1:4, 1:32, check (no predator release, 0 x), and then 1:2 (Table 1, Figure 9). Four ranks of plant condition are discernable according to predator release ratio: a) 1:16, b) 1:8 and 1:4, c) 1:4 and 1:32, and control and 1:2. It is suggested that higher predator release ratios may not be the best for the control of prey and optimum plant conditions. There appears to be a limitation or optimal predator release ratio (1:16) for control of spider mite population in order to institute the best management strategy. A predicted release ratio of prey-predator is discussed in Chapter 4. The mean spider mite population density that occurred on leaves can be grouped into five ranks: a) check (2.27), b) 1:2 and 1:4, 1:8, c) 1:4, 1:16, d) 1:32 and 1:128, and e) 1:64. Although check plots showed the lowest spider mite density over the season, the seasonal plant condition was ranked as the worst; whereas 1:32 and 1:16 predator release ratios showed the highest spider

mite density. There is no simple criterion to measure and determine which predator release ratio at introduction is the best for pest management purposes, however, the 'effective index' shows that the greatest potential lies in 1:16 predator release ratio (Figure 7). Therefore, the best predator release ratio for control of Tetranychus urticae Koch and the maintenance of plant condition in this study was 1:16.

Table 3 shows the highest mean of predator density over the season is 1:64. There was no significant difference among 1:2, 1:4, 1:8, and 1:16 ratios of predator release plots (Tables 1 and 3). The behavior and functional responses of the predator to prey population will be explained later.

Effect of nematicides. The condition of plants treated with CGA-12223 was far superior to those treated with either ethoprop or carbofuran, because of their influence on mite population (Table 4). Ethoprop was only slightly effective on suppression of mite population. As for effect on pest and predator population, CGA-12223 suppressed both spider mite and predatory mite populations, as did ethoprop (Table 4), whereas carbofuran did not suppress either spider mite or predatory mite populations (Table 4). According to the pest management (potential) value in Table 4, CGA-12223 is the best chemical to use in an integrated pest control management program for spider mites.

Effect of fertilizer. The higher ammonium nitrate level of four lbs per plot enhanced plant condition, reflected by the number of leaves per plant, but there was no evidence that ammonium nitrate level influenced pest populations. Comparison of predator population densities over the season for the three different fertility levels showed that the high rate of ammonium nitrate was superior to the low rate in maintaining predatory

density. Even though the pest population density on plants grown on low and high ammonium nitrate levels was similar, the number of leaves per plant was much greater at the higher level.

Effect of plant sources The average number of leaves on the California produced plants was higher than that on plants from North Carolina, and seasonal pest population densities on both the California and the North Carolina sources were much less than those on the Florida produced plants. Although the California strawberry plants supported higher spider mite populations than those of the North Carolina plants, this source was more tolerant to mite damage than the North Carolina source as indicated by the plant condition in Table 2.

Consequently, the best pest management strategy integrating biological control with soil treatment, fertilizer and plant source indicates that the greatest potential lies with a California produced plant grown in soil treated with CGA-12223, and increased ammonium nitrate (four lbs per plot) fertilizer and an initial release of predator at a ratio of one predator to sixteen prey.

Interactive Effects Among the Experimental Variables

Comparison of interactions among plant condition, pest population density and predator release ratio is very complicated. Therefore, the interactions of each variable with initial predator release ratio will be considered.

Effect of initial predator release ratio and plant sources. Comparison of seasonal plant condition and pest population density showed that a 1:16 predator release ratio on the California grown plants was the best combination and a 0 predator release ratio on the North Carolina grown plants was the poorest combination (Table 5). However, when sea-

sonal responses of the plant (i.e. leaf numbers) are plotted against the initial predator release ratios, the plotted graph is a normal bell-shaped distribution for either source of plants, California or North Carolina. The California plants with a 1:64 release ratio had the highest spider mite population count and the California plants with 1:2, 1:4, 1:16, 1:32 had the lowest counts with the exception of the control plot. Therefore, it is evident that the California plants which have both higher leaf count and mite population have a higher tolerance level to mite damage or a higher recovery rate after damage by spider mites than the other plants tested. This indicates that the California plants have a high pest load capacity to the spider mite population. Neither high nor low initial predator release ratio plants showed that a good plant condition could be correlated with spider mite density (Figure 7). The check plot of the North Carolina plants which had low spider mite density and few leaves per plant indicated that a small seasonal spider mite density was not necessarily the result of predator suppression of the spider mite population. Low populations also result from deterioration of plants due to earlier damage by high spider mite density with long periods of damage (Figure 5f).

Effect of initial predator release ratio and nematicides. Better plant condition was recorded in plots treated with CGA-12223 nematicide and 1:8, 1:16, and 1:32 initial predator release. All combinations of nematicide and predator density were much better than the control when plant condition was measured. The nematicide applied prior to mulching had no influence on the predator population, but did have an influence on the host plant and the spider mite population. The nematicide CGA-12223 is the best for enhancing plant condition and preventing deterioration of plants through the control of mites, nematodes, and soil-inhabiting

insects. Among the various combinations, CGA-12223 with 1:32 through 1:8 initial predator release ratios resulted in the best plant condition.

The spider mite population during the study period on CGA-12223 treated plants regardless of predator introduction densities was highest among all the treatment combinations. In addition to the effectiveness of CGA-12223 in preventing plant deterioration, it is also seen that ethoprop and carbofuran have a significant influence on enhancement of plant condition (Table 6). The CGA-12223 with 1:8 to 1:32 initial predator release ratios were the combinations contributing to the best plants. The enhanced plant condition was able to support a high spider mite increase rate. With a high spider mite increase rate, the initial predator release ratio can prevent the spider mite populations from reaching the injury threshold. The lowest spider mite densities and the worst plant conditions were found in no nematicide treated and no predator release plots. Consequently, the best combinations of nematicides and initial predator release ratios would be able to enhance the plant condition, but did not necessarily have the lowest spider mite density. These combinations (CGA-12223 with 1:8, 1:16, or 1:32) provide sufficient control of spider mites below a threshold, and consequently, suppress the seasonal average spider mite population to less than thirteen individuals per leaf. The effect of mite suppression is to allow maximum enhancement to the plant condition (Figures 2, 5, and 6). With the other treatment combinations, either the initial predator release ratio was too low to obtain sufficient control of spider mite populations in time to prevent irreversible damage (Figure 5e) or the initial predator release ratio was too high, resulting in near total annihilation of prey to be followed

by predator starvation and elimination. Surviving spider mites or immigrants then initiate new colonies. The new populations free from predator pressure increase to high densities which resulted in decreased plant conditions (Figure 5a)

Functional Responses and Dynamics of Prey and Predator Population and Plant Condition

The host plant condition of the strawberry plant, i e the number of active photosynthesizing leaves, is negatively correlated with the magnitude of the spider mite density on the plant during the previous week (Table 8). The response of strawberry plants, measured by the number of leaves, to spider mite density is delayed three to four weeks, i e the spider mite population exceeds 'past load capacity' (Chapter 5), then the plant condition is going to decrease gradually through a three to four week time interval (Figures 5a, 5b, 5c, 5d, and 5e) The converse is also true, i e minimum mite population densities result in better plants three to four weeks later The present spider mite population density on the host is positively correlated with the population level in each of the past four weeks except week two. Shih et al. (1976a) reported that the twospotted spider mite has a mean generation time of 13.6 days and peaks of ovipositian at four to nine days after emergence of female. Therefore the spider mite population cycle should occur within a three-week interval. This is indicated in Table 8 where more than a 0.20 positive correlation coefficient exists between any two populations within a three-week interval. The correlation was also significant between two populations of the spider mites in successive weeks. The highly significant correlation between mite population at a three-week and a one-week difference is due to the cyclic generation occurrence

and shorter life history of the spider mite, respectively. The negative correlation between densities of mite populations of two weeks apart may be explained based on the life history and dispersal behavior of young adult mites and the predatory behavior of *P. macropilis*. The shortest life cycle of a spider mite is about seven days (Shih *et al.*, 1976a). On a heavily populated strawberry plant the large number of new eggs become new adults in about a week, thus the high density in the following week. However, young adult spider mites become highly active about a day after eclosion and most migrate from the plant. Also the egg laying capacity of female spider mites falls drastically about two day after eclosion. Therefore, this reduced egg production together with the mass exodus of offspring creates a very low population density two weeks after the initial high density on the plant. The spider mite's predator, *P. macropilis*, is attracted to areas of high spider mite density. This predator multiplies on the plant and after one week, when their offspring appear, reaches a high population number. Their predation also helps to reduce the spider mite population. The details of the oscillations of two populations are described in Chapter 6. Since predator population is strongly correlated with seasonal average spider mite population instead of the seasonal average plant condition, there is no evidence to suggest the predator release directly enhances the plant condition.

Shih *et al.* (1976b) showed that *P. macropilis* has a high population increase rate and a high potential for controlling the spider mite population. Table 7 indicates that the predator population density is significantly and positively correlated to the present prey population density and that of the preceding two weeks, but not that of three or four weeks

pest. Therefore a population of spider mites may initially be free of predation, but once present, the predators increase very rapidly and reduce the prey density within two weeks (Table 7, Figure 5).

The practical strategy for spider mite control on strawberry is to maintain the spider mite population instead of eliminating it. Even though the population density of spider mites at the beginning of the experiment was high, satisfactory control of the spider mite population and a good plant condition were achieved from predators released at a 1:16 ratio. The functional and dynamic responses of spider mites as well as their predator populations suggested that the timing of acaricide applications are very important. In order to minimize the effect of the predaceous mites, we can suppress the spider mites if an acaricide is applied at two-week intervals instead of one-week intervals. An alternative control measure to chemical control is a promising predator P. macropilis for spider mite control on strawberry (Shih et al., 1976b). However, the timing and release technique for using P. macropilis needs to be refined. P. macropilis released at low prey density would definitely conserve the cost of rearing and labor to release them but the techniques would require close monitoring of field populations.

CHAPTER 4
THE HYPOTHETICAL PREDICTION OF BEST *PHYTOSEIULUS MACROPILIS* (BANKS) DENSITY ON CONTROLLING TWOSPOTTED SPIDER MITE, *TETRANYCHUS URTICAE* KOCH, AT INTRODUCTION

Predator density is critical in the successful biocontrol of spider mites. Pruszynski (1973) showed that the predation potential of *Phytoseiulus persimilis* Athias-Henriot is a logistic function, i.e. predatory rate increased when prey density increased to an upper limit. Svenson (1973) reported that spider mite control in glasshouses was possible with *P. persimilis* on a large scale in Sweden. Laing and Osborn (1974) studied the functional and numerical responses of the predatory mites, *P. persimilis*, *Metaseiulus occidentalis* (Nesbitt), and *Amblyseius chilensis* (Dosse), and showed that there were no prey-predator interferent effects. The prey-predator interactions were plotted as dome-shaped response curves described by Holling (1961). Burnett (1971) reported that *Amblyseiulus fallacis* (Garman) will reduce natural populations of *T. urticae* over a range of densities, provided that suitable temperature conditions prevail for a sufficient time. Oatman *et al.* (1968) and McMurtry (1966) reported that release of 320,000 *P. persimilis* per acre significantly affected spider mite populations before the spider mite density reached one mite per leaf. However, they gave no data to show the initial actual or relative population densities and ratios of predator and prey at time of release.

Successful control of spider mites depends largely on maintaining the critical balance between predator and prey with regard to initial predator-prey ratio at the time of predator introduction as previously

described in Chapter 3. Hussey et al. (1965) and Parr and Hussey (1967) indicated that satisfactory spider mite manipulation depends upon time of predator release and density of predator at introduction. The number of predators released depended upon neither actual nor relative population density of prey, but depended upon the number of plants per given area at one week after inoculation with thirty spider mites (Parr and Hussey, 1967). However, they concluded that 'several' predators on every fifth plant was the most economic and efficient density at introduction for control of spider mites. In this Chapter, we shall attempt to estimate the relationship between initial predator density and seasonal plant condition or pest population using mathematical models. The estimation is performed by fitting the models to observed data using regression techniques.

Materials and Methods

The experimental design, materials and methods are as described in Experiment IA, Chapter 2. The model developed was based on the assumption that there is a correlation or relationship between the seasonal plant condition and pest population density and the predator density at introduction. A simplified hypothetical causal network among the "inputs," i.e. plant condition level and spider mite population density, is depicted in Figure 8. The arrows indicate directions of causation. Predatory mites directly affect spider mite density and the latter directly affects the plant condition. The plant condition indirectly responds to the predator density when the spider mite is present. These hypothetical interactions may be represented by equations 4.1, 4.2, and 4.3. In these equations, subscript i denotes the plot in which the value

of the variables was determined and u_{1ti}, u_{2ti}, and u_{3ti} are disturbance or error terms for equations 4 1, 4 2, and 4 3, respectively, and are assumed to be a random quality coming from a normal distribution with mean zero and standard deviation σ

$$PC = f\ (S_1,\ u_{1ti}) \tag{4 1}$$

$$S_1 = f\ (P_1,\ u_{2ti}) \tag{4 2}$$

$$\begin{aligned} PC &= f\ (S_1,\ u_{1ti}) \\ &= f\ (f\ (P_i,\ u_{2ti}),\ u_{1ti}) \\ &= f\ (P_1,\ u_{3ti}) \end{aligned} \tag{4 3}$$

In equations 4 1 and 4 2 respectively, PC and S are considered as endogenous variables, and S and P as predetermined variables In other words, PC and S are determined by S and P respectively through the functional relationships. In a real world situation, the observed results are sum of the direct effects of predetermined variables on endogenous variables For example, the plant condition observed in plot i is the sum of the negative indirect effects of spider mite feeding density and the positive indirect effect of predator density which arises because of the spider mite density. However, for simplification, we shall measure the plant condition only as the effect of the predetermined variables of predator density

A simple cubic functional specification was used in the study to estimate the effects of predetermined variables on endogenous variables.

The model equations presented for discussion as follows

$$Y_1 = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_1^3 + u_1 \qquad (4.4)$$

$$Y_2 = \beta_0 + \beta_1 X_1 + \beta_2 X_1^2 + \beta_3 X_1^3 + u_1 \qquad (4.5)$$

Where

- Y_1 : seasonal average number of leaves per plant,
- Y_2 : seasonal average number of spider mites per leaf
- X_1 : initial predator density times 32 at introduction, i.e. (number of predators/number of prey) x 32.
- β_i : the effect or average influence on Y_i of a unit change in X_i when all other X's are fixed.
- u_i : disturbance term or random error, assumed to be normally distributed with mean equal to 0 and variance equal to σ^2

Table 1 gives the mean and standard deviation of the values corresponding to each initial predator-prey ratio. The observations with the large value of the standard deviation are considered or assumed to be less reliable than are the others with smaller standard deviation values. In the regression analysis therefore, a weighted least square analysis is performed to adjust for the level of dependability of each predetermined variable (Draper and Smith, 1968). Also, a corresponding unweighted least square analysis is performed to allow a comparison with the weighted regression model to be made.

Results and Discussion

Polynomial regression analysis using weighted and unweighted least squares produced four regression lines that depict some relationship between the dependent variables (seasonal average number of leaves per

plant and seasonal average number of spider mites per leaf) and the independent variable (predator-prey ratio at introduction). These four multiple regression lines are:

Model 1. Weighted regression line for plant condition

$$Y_1 = 25.1164 + 4.8826 (X \times 32) - 0.8071 (X \times 32)^2 + 0.0302 (X \times 32)^3 \quad (4.6)$$

$$R^2 = 0.899$$

$$P < 0.15 \quad (F\text{-value} = 5.919)$$

Where

Y_1 = seasonal average number of leaves per plant.

X = initial predator-prey ratio (number of predators/number of prey at introduction).

Model 2 Unweighted regression line for plant condition

$$Y_1 = 22.8894 + 6.7604 (X \times 32) - 1.1086 (X \times 32)^2 + 0.0423 (X \times 32)^3 \quad (4.7)$$

$$R^2 = 0.695$$

$$P < 0.25 \quad (F\text{-value} = 1.517)$$

Where Y_1 and X are as defined in Model 1

Model 3 Weighted regression line for spider mite density:

$$Y_2 = 25.9342 + 6.8343 (X \times 32) - 0.9127 (X \times 32)^2 + 0.0332 (X \times 32)^3 \quad (4.8)$$

$$R^2 = 0.946$$

$$P < 0.09 \quad (F\text{-value} = 11.683)$$

Where

Y_2 : seasonal average number of spider mites per leaf,

X : initial predator-prey ratio (number of predators/number of prey at introduction)

Model 4. Unweighted regression line for spider mite density

$$Y_2 = 36.8890 + 8.6047\ (X \times 32) - 1.6404\ (X \times 32)^2 + 0.0692\ (X \times 32)^3 \qquad (4.9)$$

$$R^2 = 0.151$$

$$P < 0.50 \qquad (\text{F-value} = 0.218)$$

Where Y_2 and X are as defined in Model 3

The maximum and/or the minimum number of leaves per plant (plant condition) can be estimated from equations 4.6 and 4.7 by setting the first derivatives of these equations equal to zero and solving them. Because the R-square value of the equation 4.7 (unweighted least square model) is small, only the weighted regression model, i.e. equation 4.6 was used to calculated the best release ratio corresponding to the optimum plant condition. The first derivative of equation 4.6 is

$$Y' = \frac{dy}{d(X \times 32)} = 4.8826 - 1.6142\ (X \times 32) + 0.0506\ (X \times 32)^2$$

and upon setting the derivative equal to zero, the resulting values (roots) of $(X \times 32)$ are

$$(X \times 32) = 13.955 \qquad \text{and} \qquad (X \times 32) = 3.8618$$

The values of the release ratio X and the corresponding estimated plant condition values are

$$X = 13.955/32 = 1/2.293 \text{ (predator/prey)}, \quad Y = 18.147$$

$$X = 3.862/32 = 1/8.286 \text{ (predator/prey)}, \quad Y = 33.673$$

Based on these values the estimated optimum initial predator to prey ratio at introduction, derived from the equation 4.6 of plant condition, is 1:8.286 (Figure 9).

Model 4 has small R-square (0.151) and F (0.118) values (Figure 10) and is consequently not discussed. However, it is used to perform a comparison with the unweighted regression model. The seasonal spider mite density is positively correlated with seasonal plant condition as was discussed in Chapter 3. Therefore the choice of best predator-prey ratio at predator release is dependent upon (1) the highest seasonal average population density of spider mites, which is always found with the best plant condition, because of the potential support a healthy plant offers to pests, and (2) the predicted upper limit of seasonal spider mite density, which cannot exceed the highest seasonal spider mite density from any given release ratio. This upper limit is estimated to be 1:6 (predator:prey) (Figure 10) from equation 4.8, which is solved in the same way as equation 4.6. In conclusion, the optimal plant condition can be maintained by release of the predator at a predator to prey ratio of either 1:8 or 1:6 at introduction depending upon whether the plant condition is the response observed or density of spider mites is the dependent response. Predators being released at higher or lower initial predator-prey ratios do not result in better plant condition.

CHAPTER 5
CAPACITY OF STRAWBERRY PLANTS TO WITHSTAND TWOSPOTTED SPIDER MITES, *TETRANYCHUS URTICAE* KOCH

Considerable research has been done in population ecology. The following pertinent theories of Nicholson, Andrewartha and Birch, Milne, Chitty, and Pimentel are discussed: (A) Nicholson (1954) indicated that an animal population might be regulated by intraspecific competition, i.e. by 'requisites' necessary for the growth and multiplication of organism, and used the term, 'density factors', for the functional relations which exist between requisites and the population numbers of that species. (B) Andrewartha and Birch (1954) stated that animal population might be limited in three ways: (1) by shortage of resources, (2) by inaccessibility of these material resources relative to the animal's capacities for dispersal and searching, and (3) by shortage of time when the intrinsic rate of increase (r) is positive. (C) Milne (1957a, 1957b, 1962) emphasized the influence of environmental conditions by stressing the negative density relationship to account for natural control. (D) Chitty (1960) reported that a population is numerically 'self-regulating' through a genetically-induced allele which may be inverse to the average vitality of the individuals in a population and population density. (E) Pimentel (1961) emphasized mutual adaptation between the inherent properties of species and their food resources or natural enemies. In other words, he applied the evolutionary principles to the problems of population dynamics by proposing a genetic feed-back mechanism for the determina-

tion of numbers. Theoretical considerations of population regulation in a simple experimental system and in complex natural systems are quite different. In a simple situation, population self-regulation and factors governing population growth and maintenance are studied. However, in a complex situation, the influences of climatic, edaphic, and biotic factors, population movement toward equilibrium, control of pests at an economic level, natural selection, and population dynamics must be considered.

Population dynamics deals with energy flows which govern movements of matter through a population, from the environment and back again. A population could theoretically expand indefinitely provided that food and habitat are in infinite supply. When either is limited, mortality tends to adjust the population accordingly, i.e. for the death of some individuals enhances the ability of survivors to obtain better resources (Lloyd, 1968, Nicholson, 1933, Pearl, 1926, Chapman, 1928). To achieve population balance, the controlling factors should act more severely against an average individual when the population density is high, and less severely against the individual when the density is low (Nicholson, 1933, 1954). Nicholson (1954) illustrated the relationships between population density and environmental factors, but did not indicate how these factors governed population balance.

This chapter will be concerned with the influence of plant condition on mite population density. The host strawberry plant affects spider mites not only by providing them directly or indirectly with food, but also by furnishing a habitat with a favorable microclimate. Conceivably, under confinement, the condition of the strawberry plants could signifi-

cantly influence population density to spider mites

The question of what is the maximum pest load that can be tolerated by a strawberry plant without change in host plant condition is important in understanding the population dynamics of spider mites. A 'pest load capacity' is defined as the maximum number of pests (spider mites) that plants can support without negatively affecting plant condition, while 'tolerance capacity' is the maximum number of pests that can be supported without influencing the maximum rate of improvement of plant condition, i.e. growth of new parts. Thus the plant condition improves at the same rate when a plant is free of pest as when the plant has pests but below the tolerance level. The term of 'pest load capacity' differs from the 'carrying capacity' of Verhulst (1838) and Pearl and Reed (1920). They assumed that the actual rate of increase per individual was a logistic function and was regulated by population density through decreasing 'population increase rate' and increasing 'population death rate.' Actually this self regulation of intrinsic rate of increase seldom occurs in natural conditions, because the status of the food supplies are living, reproducing plants. The limitation of food supply does regulate the intrinsic rate of increase to affect the pest population density. In this chapter, the relationships of the 'pest load capacity' and tolerance capacity' of strawberry plants are discussed.

Materials and Methods

The experimental design and materials and methods used were described previously for Experiment 1A in Chapter 2. The plant condition, number of leaves per plant, responded to the spider mite population densities after a lag, and was best described by a four-week delay function. With

this in mind, the response of plant condition at week t (PC_t) to its pest spider mite at weeks t-4, t-3, t-2, and t-1 are discussed in the following model

Multiple regression model of pest load of strawberry plant

$$Y_1 \text{ or } Y_2 = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5(X_1 \times X_2) + B_6(X_2 \times X_3) + B_7(X_3 \times X_4) + u_i$$

Where

Y_1 : the number of leaves per plant lost during the past four weeks

Y_2 : the number of leaves per plant gained during the past four weeks

$B_0, B_1 \ldots B_7$ = the effect or average influence in a one unit change of the independent variable, i.e, X_1, X_2, X_3, X_4, when all other X's are fixed

X_1 = the natural logarithm and the logarithm of number of mites per leaf at week t-4 for Y_1 and Y_2, respectively

X_2 = the natural logarithm and the logarithm of number of mites per leaf at week t-3 for Y_1 and Y_2, respectively

X_3 : the natural logarithm and the logarithm of number of mites per leaf at week t-2 for Y_1 and Y_2, respectively

X_4 : the natural logarithm and the logarithm of number of mites per leaf at week t-1 for Y_1 and Y_2, respectively

u_i : disturbance term or random error, assumed to be normally distributed with mean equal to 0 and variance equal to σ^2

Results and Discussion

Analysis of four independent variables (four spider mite population densities) at weekly differences in a period of four weeks indicated that there were two multiple regression lines which showed the correlations between the dependent variables (number of leaves lost or gained) and the independent variables (number of spider mites per leaf). These two multiple regression lines are

1 When number of leaves per plant was reduced over four week period.

$$Y_1 = 38.70 + 7.39\,X_1 + 75.41\,X_2 - 382.92\,X_3 + 21.83\,X_4 + 9.12\,(X_1 \times X_2) - 337.88\,(X_2 \times X_3) + 425.06\,(X_3 \times X_4) \quad (5.1)$$

$R^2 = 0.912$

$P = 0.0001$ (F-value = 20.708)

Where

Y_1 = the number of leaves lost during the past four weeks.

X_1, X_2, X_3, X_4 = natural logarithm of number of mites per leaf at weeks t-4, t-3, t-2, and t-1, respectively.

If assumed that the mite population density during the four weeks remained at a constant level (i.e. $X = X_1 = X_2 = X_3 = X_4$), and that Y = 0, (i.e. plant condition did not chang due to the presence of the spider mite population), the 'pest load capacity' can be solved from equation 5.1 as a quadratic

$$(425.06\,X^2 - 337.88\,X^2 + 0.12\,X^2) + (21.83\,X - 382.92\,X + 75.41\,X + 7.39\,X) + 38.70 = 0$$

$$87.30\,X^2 - 278.29\,X + 38.70 = 0 \qquad (5.1a)$$

therefore $X = 0.1457$, $e^X = e^{0.1457} \doteq 1$ (mites/leaf)

or $X = 3.042$, $e^X = e^{3.0420} \doteq 21$ (mites/leaf)

2. When number of leaves per plant was increased over four week period.

$$Y_2 = -14.43 - 44.66\,X_1 - 20.65\,X_2 + 67.19\,X_3 + 127.80\,X_4$$
$$+ 20.03\,(X_1 \times X_2) - 28.93\,(X_2 \times X_3) - 71.92\,(X_3 \times X_4) \qquad (5.2)$$

$R^2 = 86.84$

$P = 0.0005$ (F-value = 14.75)

Where

Y_2 : the number of leaves gained per plant during the past four weeks.

X_1, X_2, X_3, X_4 : the logarithm of number of mites per leaf at weeks t-4, t-3, t-2, and t-1, respectively.

Again, if $X = X_1 = X_2 = X_3 = X_4$, and $Y_2 = 0$, the 'pest load capacity' can be solved from equation 5.2

$$Y_2 = -14.43 - 44.66\,X - 20.65\,X + 67.19\,X + 127.80\,X + 20.03\,X^2 - 28.83\,X^2 - 71.92\,X^2 = 0$$

$$-80.82\,X^2 + 129.69\,X - 14.43 = 0 \qquad (5.2a)$$

therefore $X = 1.4843$, $10^X \doteq 30$ (mites/leaf)

or $X = 0.12$, $10^X = 1$ (mites/leaf)

The 'pest load capacity' calculated from plant condition is either approximately 30 mites per leaf from equation 5.2 with improving plant condition or approximately 21 mites per leaf from equation 5.1 with declining plant condition (Figure 11). The pest load level (30 mites per leaf) during the improving phase of plant condition is much higher than that of the level (21 mites per leaf) during the declining phase of plant condition. This suggests that strawberry plants can better withstand spider mite damage during leaf growth.

At the point of intercept of the two regression lines from equation 5.1 and 5.2, the number of leaves per plant gained or lost is equal (Figure 11). Therefore the value of X at this point provides a third value for 'pest load capacity'. This intercept is calculated as follows:

let(1) the spider mite population during the past four weeks be fixed (i.e. $X = X_1 = X_2 = X_3 = X_4$),

(2) the number of leaves per plant gained and lost be equal ($Y_1 = Y_2$).

then

$$87.3\,(\ln X)^2 - 278.29\,(\ln X) + 38.70 = -80.82\,(\log X)^2 + 129.68\,(\log X) - 14.43$$

$$543.68\,(\log X)^2 - 770.47\,(\log X) + 53.13 = 0 \qquad (5.3)$$

therefore

$\log X = 0.073,\qquad X = 10^{0.073} \doteq 1$ (mites/leaf)

or

$\log X = 1.344,\qquad X = 10^{1.344} = 22$ (mites/leaf)

The lower value is rejected and the spider mite density of approximately 22 mites per leaf is considered as a pest load capacity for the strawberry plant. Consequently the 'pest load capacity' of strawberry plant should alway fall between 21 and 30 mites per leaf.

The maximum improvement rate of plant condition (number of leaves per plant gained per four weeks), solving from the first derivatives of equation 5-1a and 5-2a, can be reached when the spider mite density is as high as 5 mites per leaf (5-1a) or 6 mites per leaf (5-2a). From the same equation, plant condition can be seen to improve but at a reduced rate when spider mite density falls below 5 or 6 mites per leaf. However, in reality, further lowering of mite density should not cause the plant condition to improve at a slower rate. Therefore spider mite densities of 5 and 6 mites per leaf are the 'tolerance capacity' of the strawberry plant when increasing and declining respectively. The 'pest load capacity' may be used to substitute the 'carrying capacity' as a regulative factor which adjusts or limits the population growth rate. Therefore 'pest load capacity' may be used to predict a population increase rate for pest management purposes using a population model. Constant presence of spider mite population is necessary to support the predator population, which can exert control on the spider mites that will migrate into the field later on. Based on 'tolerance capacity', spider mite populations should be manipulated under this population density level instead of eliminating them to achive no loss in plant growth or development rate.

CHAPTER 6

PREDICTION OF THE EQUILIBRIUM POINT OF THE FUNCTIONAL RESPONSE OF PREDATOR, *PHYTOSEIULUS MACROPILIS* (BANKS) AND ITS PREY, *TETRANYCHUS URTICAE* KOCH

The nonlinear function of a predator-prey system in which the populations of the two species are principally regulated by one of the species preying of the other has been depicted as an oscillation characterized by the Lotka-Volterra equation (Lotka, 1920, Volterra, 1931, Usher and Williamson, 1974). The equation is mathematically hypothesized under a confined predator-prey system, containing a species population of predator-prey, and a host plant (or a limited quantity of food resource) in a determined or confined space. If populations of a time series, predators at generation t (PH_t) and prey at generation t+1 (TH_{t+1}), in a confined system are plotted in a phase diagram (a two-dimension coordinate), the solutions of the Lotka-Volterra equation are closed trajectories (line connecting points in time) around the equilibrium point (Canale, 1970, Gilpin and Rosenweig, 1972, May, 1972, 1974). A stable limit cycle is like a stable equilibrium point except that the trajectory spirals in toward a circle instead of toward a single point. When disturbed, either the stable limit cycle or the stable equilibrium point system will tend to return to its former equilibrium. Canale (1970) plotted a phase-space-diagram (in a three-dimensional coordinate for glucose substrate, prey and predator with the plotted points connected in time series) from a chemostat culture of a predator-prey system and showed that the

trajectory tends to spiral toward a point of a limit circle. An inward or outward trajectory spiraling toward a stable point or circle is obtained when the initial population ratio and densities of predator and prey are near equilibrium, otherwise, a contray or no spiral trajectory will occur. When an initial predator-prey ratio is close to or reaches an equilibrium point or circle, the last observation point of a time-series data set in a coordinate is closer to the center of the spiral than that of any other initial predator-prey ratios.

In this study, the connecting points in time in a phase diagram from an initial predator-prey ratio can be fitted into a spiral function by a regression model. The fit of a regression line to a set of points from this model can be used to determine which initial predator-prey ratio is the closest one to the equilibrium point or circle. However, technical problems exist because (1) the last observation point in a time-series of data set in a predator (PN_t) and prey (TN_t) coordinate is not necessarily located on the origin of a coordinate and (2) the formula for the "spiral of Archimedes" used in this study either centers or recedes from the origin of the coordinate (Bers, 1969). Therefore, the origin of the coordinate has to coincide with a hypothetical spiral center of an observed data set from one of the initial predator-prey ratios. Since the hypothetical spiral center is unknown, a gravity center of the observed points in time-series of each initial predator-prey ratio is used in this study. The gravity center is the point which can be calculated from the time-series data set points and which represents these points better in stability than any original point of observations. Therefore in an initial predator-prey ratio the values of observation

points on PN_t plotted against TN_{t+1} of a time-series can be transformed from the origin of coordinate to the new origin of coordinate. The gravity center of an initial predator-prey ratio is used to be the origin of the new coordinates.

The formula for the "spiral of Archimedes" is $r = K\theta$, where r is the radius of a spiral from any point on the trajectory to the origin of coordinate, K is constant, and θ is the angle between the radius and the abscissa of the coordinate (Figure 14). As indicated in Chapter 3, the spider mite and its predator complete their life cycles in about one week. Therefore the response of the prey to the predator with a one-week delay is one generation difference between population density of predator and prey. In this study, the coordinates are determined by population density of T. urticae at week t+1 (TN_{t+1}) and population density of P. macropilis at week t (PN_t). From the mathematical calculation, r and θ can be obtained for corresponding points of a set of data for any initial predator-prey ratio. From the "spiral of Archimedes" the θ (angle between radius and abscissa) is assumed to be the independent variable, and r is the dependent variable. Based on this assumption, a regression model, either a linear or a curvi-polynomial equation, can be used to fit a set of points in an initial predator-prey ratio. The estimated regression line among the tested initial predator-prey ratios that results in the best fit of the spiral function is then determined by the highest value of R-square.

The best fitting regression model is used to predict the closest equilibrium point or limit circle if the corresponding initial predator-prey ratio can reach equilibrium after several generations. The purpose

of this study then is to provide data and a sound basis for an eventual theory to predict population densities and establish release ratios in a biological control strategy. A delay functional response, i.e. response of prey to predator with a generation difference, is substituted for functional responses (Solomon, 1949, 1957, Holling, 1966) in this study to explain the predator-prey system.

Materials and Methods

The initial predator-prey ratios in this study included 1:2, 1:4, 1:8, 1:16, 1:32, 1:64, and 1:128. Population densities of predator and prey in plots with different initial predator-prey ratios, i.e. the ratios between predators released into the plots and prey already present in the plots, were established weekly for nine weeks for the first five ratios and for six weeks for the latter two ratios.

The weekly predator-prey ratio plotted against time (week) is the traditional approach to show an equilibrium point (Figure 12). The data were transformed (PN_t, TN_{t+1}) and the delay density dependent functions with phase-space-diagram (Conele, 1970, May, 1974) were used to determine which initial predator-prey ratio lay closest to the equilibrium point. The original population values for predator and prey were then transferred to plot both populations in a phase diagram using formulae 1 and 2.

(1) PN_t (Transformed values for population density of predator)

$= \ln((\text{No. of predators per leaf at week t}) \times 10 + 1)$

(2) TN_{t+1} (Transformed values for population density of prey)

$= \ln((\text{No. of prey per leaf at week t} + 1) \times 100 + 1)$

The average life cycle of the spider mite, i.e. from egg to egg, is about 6.3 days. Therefore, for the purpose of this study, the predator and prey in week t and in week t + 1 are considered a generation apart, although in reality both populations have overlapping generations. The transformed value for predator density at week t (PN_t) was plotted against the transformed value of prey density at week t + 1 (TN_{t+1}) and the resultant points for consecutive weeks linked in a time series (Figure 13). An inward trajectory spiral means that the initial predator-prey ratio is closest to the equilibrium point or limit circle. This system is, therefore, quite different from the density dependent system of Smith (1935, 1937), but is identical to a delay density dependent system (Malling, 1966, Solomon, 1949, Varley, 1947, Varley *et al.*, 1974).

In order to fit the "spiral of Archimedes," the values of the data points were transferred from the origin of coordinate ($O(0, 0)$) to a new position, i.e. to the gravity center ($O\,(TN_1, PN_{1-1})$) (Figure 14). Therefore the radius ($\bar{r}$) from any point on the trajectory to the new spiral center and the angle ($\bar{\theta}$) between $\bar{r}$ and abscissa can be calculated as follows

$$\bar{r} = \sqrt{r^2 + r_0^2 - 2\, r\, r_0 \cos(\theta - \theta_0)} \qquad (6.1)$$

and

$$\begin{aligned} \bar{\theta} &= \theta_0 + \gamma + (\theta - \theta_0) \\ &= \theta + \gamma \\ &= \theta + \pi - \sin^{-1}\left(\frac{r \sin(\theta - \theta_0)}{\bar{r}}\right) \qquad (6.2) \end{aligned}$$

Thus the equation for the basic spiral, with its center at the new origin of coordinates, used for the regression model is

$$\bar{r} = K\,\bar{\theta} \qquad (6.3)$$

where $\bar{r}$ and $\bar{\theta}$ are defined as in Figure 14 and K is a constant. Equation 6.3 satisfies the hypothesis of the spiral that $\bar{r}$ is the function of $\bar{\theta}$. Therefore the regression model can be applied to test which observation points among the initial predator-prey ratios is closest to the equilibrium point or limit circle.

Other than the linear regression model, there are regression models with higher order polynomial equations that also have the characteristics of a spiral trajectory but whose angle of trajectory line increases faster and approaches an equilibrium point (spiral center) quicker than that of lower order polynomial equations.

The regression models discussed below are used to determine which initial predator-prey ratio best fits the described conditions.

Model A. Linear regression model.

$$\bar{r} = B_0 + B_1\,\bar{\theta} + u_i \qquad (6.4)$$

where

$\bar{r}$ = square root of $(PN_t^2 + TN_{t+1}^2)$, i.e. the radius from a point of spiral to its center.

B_0 = the average response when $\bar{\theta} = 0$

B_1 = the average influence of one unit change in $\bar{\theta}$

$\bar{\theta}$ = the angle between $\bar{r}$ and abscissa of a coordinate of its X-axis, TN_{t+1}, and Y-axis, PN_t.

u_i the disturbance term ar random error, assumed to be normally distributed with mean equals to 0 and variance equals to σ^2

Model B. Quadratic regression model.

$$\overline{r} = B_0 + B_1 \overline{B} + B_2 \overline{B}^2 + u_i \qquad (6.5)$$

where $\overline{r}$, B_0, B_1, $\overline{B}$, and u_i are the same as described in Model A

Model C. Cubic regression model.

$$\overline{r} = B_0 + B_1 \overline{B} + B_2 \overline{B}^2 + B_3 \overline{B}^3 + u_i \qquad (6.6)$$

where $\overline{r}$, B_0, B_1, $\overline{B}$, and u_i are the same as described in Model A.

Model D. Multiple curvi-polynomial regression model.

$$1.\quad \overline{r}^2 = B_0 + B_1 \overline{B} + B_2 \overline{B}^2 + u_i \qquad (6.7)$$

$$2.\quad \overline{r}^2 = B_0 + B_1 \overline{B} + B_2 \overline{B}^2 + B_3 \overline{B}^3 + u_i \qquad (6.8)$$

where $\overline{r}$, $\overline{B}$, B_0, B_1, and u_i are the same as described in Model A

Equations 6.4, 6.5, and 6.6 were set up to test the stable equilibrium point when population increase rate (r_m) is $0 < r_m < 2$ (May, 1972)

Results and Discussion

The traditional approach of plotting predator-prey ratio against the time for the equilibrium study is shown in Figure 12. There is no exact mathematical equation available to describe this functional re-

sponse of predator-prey ratio over time exactly in order to determine which predator-prey ratio lies closest to the equilibrium point. The regression analysis for the selection of the initial predator-prey ratio that is closest to the equilibrium point or limit circle depends upon the transformed data, translocated origin of coordinates and spiral function as shown in Appendix I and Figure 14. The results of the regression analyses of different initial predator-prey ratios are listed in Table 9. Linear and curvi-polynomial regression lines are significant at either a 0.01 or 0.05 level by the F-test. The highest R-square values found in linear, quadratic, and cubic regression line are 0.547, 0.690, and 0.801, respectively. The first two highest R-square values of Model A, the linear regression line, are found in 1:32 and 1:128 initial predator-prey ratios, but the highest R-square value of the other four regression models are found for the 1:128 ratio (Table 9). However, the R-square value of the regression line for Model A of 1:32 predator-prey ratio is only 0.547. This value is too small to indicate that the variability in the data can be adequately explained by this regression line, i.e. the least squares estimated regression line can only account for approximately 54.7% of the total variance. The statistical best fitting (highest R^2) regression lines among the tested initial predator-prey ratios over all the discussed models occurred with the 1:128 by Models B, C, and E.

An R-square value of 0.801 (P = 0.0001) is found in the 1:128 initial predator-prey ratio by Model C for the transformed data sets between PN_t and TN_{t+1}. Based on the R^2 value the initial predator-prey ratio in this study which can reach the equilibrium point or

limit circle with a spiral trajectory is 1:128. Therefore, the ratio of the equilibrium point or limit circle of the P. macropilis and T. urticae system, is at a predator-prey ratio of 1:128. The R-square value of the regression line of 1:128 in Models A and B (0.365, 0.690, respectively) is not sufficiently large enough to select either, but in Model C the R-square is 0.801. In this predator-prey system the trajectory of the spiral approaches its center more rapidly, i.e. a cubic function, instead of a linear or a quadratic function. Since the highest R-square value (0.801) is obtained from 1:128 predator-prey ratio in Model C for the regression line, the response of the prey population density can be explained as a generation or one-week delay functional response to the predator, P. macropilis, population density. The initial predator-prey ratio of 1:128 can reach or be near the equilibrium point or limit circle. When the predator, P. macropilis, is used as a biological control agent to control twospotted spider mite, the number of predators released must be dependent upon the density of prey in the field. Under natural conditions, the actual number of predators released is not directly dependent on the best initial release ratio of predator, but is dependent on the difference between the best initial release ratio and the equilibrium point. However, there should be much more intensive study of this hypothesis.

CHAPTER 7
ACARICIDE RESISTANCE IN TWOSPOTTED SPIDER MITE, TETRANYCHUS URTICAE KOCH, ON FLORIDA STRAWBERRY PLANT

The resistance of spider mites to acaricide was first reported by Smith et al. (1947). Mites resistance has been discussed from two different viewpoints. One is the biochemical mechanisms which include insensitivity of cholinesterase and increased metabolic powers to detoxify alien intruded molecules (Dittrich et al., 1974, Dittrich, 1975). The second is the genetics of resistance of mites populations, such as the recessive gene in the gene pool and how it was distributed and selected for (Dittrich, 1975). Brown (1960) reviewed the mechanisms of resistance against insecticides and described six types of chemical resistance. Physiological mechanisms of resistance were classified on the basis of behavior, structure, penetration, storage, excretion, detoxification, and decreased sensitivity by Chadwick (1955). Taylor and Smith (1956) demonstrated the genetic basis of resistance and indicated that resistance to malathion was probably based on a single factor in their Cranbury I colony of twospotted spider mite, Tetranychus urticae. Andres and Prout (1960) suggested that the resistance to parathion was also based on a single factor. The requirements for the development and maintenance of resistance include high propagation potential (Dittrich et al., 1974), cross fertilization and cross resistance (Dittrich, 1961, Ong and Ballantyne, 1974), high mutation rate (Dittrich, 1975, Helle and Van Zon,

1967), and isolation or semi-isolation of the strains selected for resistance (Dittrich, 1975).

The resistant genes of T. urticae to organophosphate appear to reside at the same locus or are closely linked loci (Cranham, 1974). Kensler and Streu (1967) reported that susceptible mites demonstrated the greatest overall reproductive capacity in that they oviposited the most eggs, and had the greatest percentage of viable eggs and the shortest life cycle. Dittrich (1961) demonstrated that by crossing resistant females and susceptible males with a weaker selection pressure would result in a population of twospotted spider mite that demonstrated decreasing resistance to demeton in later generations.

An interesting topic is the measurement of resistance increase rate of spider mite field populations under low chemical selection pressure as well as the resistant decrease rate. Overmeer et al. (1975) showed that reversion to susceptibility of spider mite to dicofol was very slow. In this study the increase in the rate of resistance and the rate of reversion to susceptibility of twospotted spider mite was tested to either a chlorinated hydrocarbon, dicofol, or an organophosphate, naled, under low selection pressure, which is the weekly chemical application with LC_{50} concentrations. As indicated in Chapter 3, the spider mite completed its life cycle in about one week. Therefore it is possible to say that selection pressure of the chemical is acting on each generation of spider mites.

Materials and Methods

The materials and methods are as described in Experiment 2 in Chapter 2.

Results and Discussion

The LC_{50} of naled and dicofol on seven generations of twospotted spider mite is listed in Tables 10 and 11. The resistance of twospotted spider mite to both naled and dicofol increased at the highest rates (38.14% and 60.30%, respectively) in the first generation subjected to the low chemical selective as defined by toxicologist. A total increase of about 140% in resistance to dicofol and 38% in resistance to naled had developed in seven generations of spider mites. Therefore it appeared that twospotted spider mites developed resistance to dicofol faster than to naled.

Cranham (1974) demonstrated that the major resistant genes of some strains of twospotted spider mites to organophosphate reside at the same locus or are closely linked loci. The genes of twospotted spider mite responsible for development of resistance to naled, an organophosphate, may be the same as that to other organophosphate chemicals shown by Cranham (1974), and Taylor and Smith (1956). The slow resistance increase rate of spider mite population to naled in this study may be explained as follows: (1) the resistant allele is recessive, therefore heterogeneity is susceptible, (2) susceptible mites have higher overall reproductive capacity in that they oviposit more eggs, and have a greater percentage of viable eggs and a shorter life cycle (Kensler and Streu, 1967).

Twospotted spider mites reared on kidney bean leaves with DDT residue have a greater ratio of females to males and higher egg production than untreated counterparts (Dittrich et al., 1974). Dittrich et al (1974) explained these phenomena as probably caused by stimulation

of small quantities of a stressor (probably a sex ratio distorter) which is responsible for the increased synthesis of DNA, which in turn accelerates sperm production which would account for the greater number of females derived from fertilized eggs. The increase in resistance rate of spider mites to dicofol may be similar to the responses of ellcited with DDT (Dittrich et al., 1974). A high mutation rate, a great propagation potential and cross fertilization in each generation, which are the characteristics of an arrhenotokous species, may also account for the development of resistance of twospotted spider mites to dicofol.

The reversion to susceptibility to naled and dicofol in twospotted spider mite occurred in the fourth generation (Tables 10,11). The twospotted spider mite population tested with naled further reduced its resistance and did not re-develop resistance until the seventh generation (Table 11). This reversion to susceptibility to these two acaricides may be due to susceptible mites producing more eggs with a greater percentage of viability (Kensler and Streu, 1967). The reduction of resistance to naled in the fourth week may be explained by a study of Dittrich (1961), who demonstrated that under the low selection pressure of a low concentration of demeton, also an organophosphate, crosses between resistant females and susceptible males of spider mites will produce offspring with lowered levels of resistance. It is also possible that this lowered resistance is due to the resistant allele being recessive.

Reversion to susceptibility of twospotted spider mites to naled is apparently fast under field conditions and it is possible that the use of naled will be valuable in a rotational spray system. The slow re-

version to susceptibility of spider mites to dicofol, a conclusion also reached by Overmeer et al. (1975), precludes its use in a rotational spray system in practical pest management. Since spider mites do not develop resistance to high levels of dicofol (Ong and Ballantyne, 1974), it is recommended that dicofol be applied in high concentrations for the control of spider mites.

CHAPTER 6
RESPONSE OF *TETRANYCHUS URTICAE* KOCH POPULATIONS TO ACARICIDES

The twospotted spider mite, a major pest of Florida strawberries, feeds on leaves and fruits and causes loss of chlorophyll, destruction of leaf tissues, and plant stunting followed by loss of yield quantity and quality. The only pest management practice recommended is the use of chemicals to suppress the development of spider mite populations. The first recommended chemical was sulfur (Brooks and Kelsheimer, 1951). As each material failed to adequately control population growth, it was subsequently replaced by dicofol, parathion (Brooks and Kelsheimer, 1961), trithion, and naled (Wolfenbarger, 1968, Poe, 1973).

Unsatisfactory management of the mite populations is caused by inadequate coverage, presence of mites during the harvest when frequent fruit picking makes the use of toxicant risky, and by the decreased effectiveness of several chemicals in field populations. Wolfenbarger (1968) provided data which suggested that populations in Florida exhibit resistance to one or more of the following chemicals: sulfurs, chlorinated hydrocarbons, and organophosphates. This resistance of twospotted spider mite to toxicant chemicals was also well documented from other areas (Andres and Prout, 1960, Cranham, 1974, Dittrich, 1961, 1975, Dittrich et al., 1974, Helle and Van Zon, 1967, Oeg and Ballantyne, 1974, Overmeer et al., 1975, Taylor and Smith, 1956). Poe (1973) demonstrated better suppression of field spider mite populations with cyclic carbamates, sulfite, and organotin acaricides than with organophosphates,

carbamates, chlorinated hydrocarbons or formamidine acaricides. He suggested that resistance was present in the field populations.

The repeated and prolonged use of a toxicant as long as it is still effective has led to the development of resistance to several chemicals. The presence of cross resistance to similar compounds within an acaricide class but not to compounds of other classes was documented (Brown, 1969, Dittrich, 1975, Ong and Ballantyne, 1974) Compounds of different chemical classes may provide better population suppression when used alternately or in combination than when either class is used alone.

Evidence of field resistance to chlorinated hydrocarbons (Table 10) and to organophosphate acaricides (Table 11) in populations of spider mites in Florida (Poe, 1973, Wolfenbarger, 1968) is discussed in Chapter 7. This evidence has led to research for more effective use of the registered acaricides which include those to which resistance is apparent.

Consequently, experiments were conducted to determine if spider mite populations can be more effectively suppressed when a chlorinated hydrocarbon (dicofol), an organophosphate (naled), an organotin (Vendex®), or a sulfite (Omite®) are used alone repeatedly, or when tank mixed combinations are used.

Materials and Methods

Materials and methods are as described in Experiment 3 in Chapter 2.

Results and Discussion

Development of Resistance of Spider Mite Populations to Acaricides

The first application of chemicals reduced the population more effectively than subsequent applications (Table 12). A possible explanation is that after being exposed to the selection pressure of the first

spray of either dicofol or naled, the population of spider mites rapidly developed their resistance to these acaricides. This resulted in lower effectiveness of these chemicals to the mites in later generations (Table 12).

Plots treated with a mixture of dicofol (EC) and naled (EC) each at a lower rate than either used alone, had greater reduction of seasonal average spider mite density and greater daily percentage mortality than plots treated with a higher rate of naled (EC) alone but not dicofol (EC) (Table 12, 19). The initial effect of naled (8EC), dicofol (1.6 EC), and a combination of the two acaricides on spider mite populations was the highest among all tested chemicals (Table 13, 14, 15). Dicofol (WP) and naled (EC) were the least effective chemicals for suppressing seasonal spider mite populations (Table 12). This high initial and low seasonal effects of naled (1.6 EC) on spider mite population density may be due to the quick action and high concentration of the chemical.

Influence of Acaricides on Spider Mite Populations: Speed and Duration

In all cases except these plots treated with either naled (8 EC) or a combination of dicofol (1.6 EC), naled (8 EC) and Omite (30 WP), the reduction of spider mite population densities to the lowest level was at three to five days after treatment, followed by an increase in population densities (Figure 15, Table 15, 16, 17, 18). It is hypothesized that the effect of the chemicals in suppressing spider mite populations probably lasted for only three to five days. In plots treated with omite (30 WP), dicofol (35 WP), and their combination, spider mite population density first increased for two to three days after the spray (Table 14, 15, 16), and then decreased (Figure 15A, C, E, Table 16, 17,

16). However, in plots treated with dicofol (1.6 EC) spider mite population density first decreased for three days and then increased until it peaked at day six after application (Figure 15J). In both plots treated with dicofol (WP) and dicofol (EC) the population densities of spider mites decreased from the sixth to eighth day after treatment (Figure 15A, 15J). Dicofol (EC) proved superior to dicofol (WP) (Table 12, 15) in suppressing seasonal development of spider mite populations and in quickly killing a large number of spider mites. This difference in performance could result from the better application characteristics of an emulsifiable concentrate.

Effects of Acaricides and Their Combinations

There was no phytotoxicity observed on tested strawberry plants and all tank mixed combinations of the acaricides appeared to be physically compatible. Seasonal spider mite populations varied greatly in Experiment 3A. However, all of the treatments, except those of dicofol (WP) and naled (EC), provided better suppression of seasonal average spider mite populations than the checks (Table 12).

Combinations containing lower rates of all three classes of chemicals provided suppression of seasonal population density which was comparable to either dicofol (EC) or omite (WP) used alone at their highest rate (Table 12). The use of combinations of dicofol (WP) or naled (EC) with omite (WP) resulted in significantly greater population suppression for the entire season than that resulting from dicofol (WP) or naled (EC) used alone at greater concentrations (Table 12). However, the use of a combination of lower rates of dicofol (EC), naled (EC), and omite (WP), and that of lower rates of naled (EC) and omite (WP), provided a poorer control of spider mite populations at the beginning of the

chemical program (Table 19, 20). These results may be due to the following factors: (1) the probability of spider mite populations developing resistance to all three chemicals or to two chemicals is generally less than to any one chemical; (2) a possible incompatible effect in a mixture of two different formulations, i.e. EC and WP; (3) antagonistic effect of these three or two chemicals (Table 20, Figure 16) may result in a poorer initial suppression of spider mite population than from either one of the chemicals used alone. The most effective among combinations of two chemicals appeared to be dicofol (WP) with omite (WP) for suppressing seasonal average population (Table 12), but there is no evidence to indicate a synergistic effect (Table 20, Figure 16).

Mixture of dicofol (WP) and omite (WP) was not significantly different from that of dicofol (EC) and naled (EC) in suppressing seasonal spider mite populations. However, a mixture of dicofol (EC) with naled (EC) is faster and more effective than that of dicofol (WP) and omite (WP) in controlling spider mite populations for short-term control purposes (Table 19). Vendex applied at the higher rate provided better suppression of spider mite populations than vendex at the lower rate (Table 19).

In conclusion, the dicofol 1.6 EC is the most effective acaricide among the tested chemicals for suppression of spider mite populations. A combination of dicofol EC and naled EC is the only one which did not significantly show antagonistic effect among the two and three acaricide combinations. Since the effects of the tested chemicals in suppressing spider mite populations probably lasted for only three to five days, repeating the use of chemicals every three to five days is necessary

to bring the population down to a desired level. Weekly or ten day applications would likely result in poor suppression or an increasing population level. The use of combinations of dicofol (WP) with omite (WP) resulted in better control of spider mite populations for long-term control strategies.

CHAPTER 5
CONCLUSION

The major purpose of this research was to seek pertinent information that would enable us to most effectively control or manipulate twospotted spider mite populations on strawberries at or below an economic threshold. Based on either the qualitative or quantitative informations obtained, we might be able to reduce the costs of control and to monitor mite damage and maintain a place in the competitive market.

From a hypothetical regression model, predator release ratios in the range of 1:8 to 1:6 are recommended. However, information on predator biology has shown that the use of P. macropilis at a 1:16 predator release ratio resulted in the best control of spider mites as reflected by plant condition. The average time required for predators to reduce the spider mite populations to below the injury level was about two weeks, after which the population stayed below this level for another four weeks. In choosing integrated control methods the spider mite population density should be determined. A high predator release ratio (1:2) is required to obtain the most rapid control of spider mites at high population densities before they can cause serious damage to the host plants, but the higher predator release ratio results in a higher cost of control. Therefore, a chemical control program may be included in the pest control strategy. The use of acaricide depends on the population density of the spider mites as well as the population density of predators.

Dicofol (1.6 EC) applied at 1 lb ai per acre is recommended for spider mite control. Due to the rapid development of resistance of spider mite populations to dicofol, a combination of lower rates of dicofol (1.6 EC) and naled (8 EC) is the alternative choice in controlling resistant spider mite populations. Side effects notwithstanding, the repeated use of acaricide on every fifth day would be the best way to suppress and to eliminate spider mite populations. However, the frequent application of chemicals would be costly and would result in higher levels of residues that would cause pollution of the environment as well as the elimination of natural enemies of the spider mites. In order to avoid these disadvantages the acaricides should be applied in an integrated program at two-week intervals instead of five-day or one-week intervals. As an alternative to chemical control, P. macropilis should be released to suppress spider mite population to below 'tolerance capacity' or 'pest load capacity' of the strawberries. This initial release should be made between two successive chemical applications that are fourteen days apart.

Cultural practices and other factors also influence plant condition and spider mite population density. Among the nematicides tested, CGA-12223 (10 G) was the most effective for the suppression of spider mite population density and in turn was the best for the plant condition. Additional ammonium nitrate applied as fertilizer also improved plant condition. California grown strawberry seedlings exhibited better plant condition and were better able to tolerate spider mites at high population densities than were plants from other sources.

Consequently, the best pest management strategy consists of integrating biological control with soil treatment, fertilizer and plant source. This research indicates that the greatest potential lies with a California produced plant grown in soil treated with CGA-12223, and increased ammonium nitrate fertilizer with an approximate initial release ratio of predator to prey of 1:8.

However, the timing and technique of release of _P. macropilis_ and timing of chemical application depend on our ability to predict the population densities of _T. urticae_, _P. macropilis_, and other strawberry pests and their natural enemies. This area needs to be intensively studied.

'Pest load capacity', the maximum population density of spider mites that can be sustained by strawberry plants without negatively effecting plant condition, may be used to predict a population increase rate for management purposes using population simulation models. Also the maximum population density of spider mites at or below the 'tolerance capacity' can be sustained by the strawberry plant without influencing the maximum rate of improvement of plant condition. In order to control twospotted spider mite population density to below a 'tolerance capacity' (5 to 6 mites per leaf) and to practice a long-term pest management, we have to suppress the spider mite population with predators as well as release spider mites into the field. The constant presence of spider mites is necessary to support the predator populations, which can exert control on spider mites that will later migrate into the field. The techniques to achieve these interactions need to be further refined.

Table 1. Seasonal responses of plant condition and twospotted spider mite and *Phytoseiulus macropilis* population densities to predator release ratio

Response	N	Predator release ratio 1:2 Mean	1:2 SD	1:4 Mean	1:4 SD	1:8 Mean	1:8 SD	1:16 Mean	1:16 SD	1:32 Mean	1:32 SD	check Mean	check SD
Plant condition (No. leaves/plant)	27	23.35	8.23	28.84	16.17	30.00	16.30	38.50	19.21	27.64	21.44	21.31	6.46
T. urticae (No. individuals/leaf)													
Egg	36	14.19	10.68	11.80	26.69	20.69	20.45	17.94	27.93	20.21	54.86	12.12	32.46
Active stages	36	22.56	24.81	27.90	12.79	18.62	11.40	25.98	48.51	49.01	128.82	10.58	28.15
Total	36	36.75	31.59	39.70	28.23	39.31	25.69	43.92	64.92	69.21	177.03	22.70	49.27
P. macropilis (No. individuals/leaf)	36	3.89	2.93	2.86	5.59	1.77	5.41	2.63	6.99	0.31	3.46	--	--
t-value of active stage eggs 1 2		1.86 (0.01)		3.08 (0.01)		-0.56 (0.30)		0.81 (0.20)		1.16 (0.05)		3.55 (0.01)	

1. Values in the parenthesis are the probabilities of type I error.
2. t-values of the check are calculated from Experiment 1B.

Table 2. Influence of ammonium nitrate and plant source on population of twospotted spider mites, predators, *Phytoseiulus macropilis*, and plant condition

Variables	Ammonium nitrate level		Source		
	4 lbs/plot Mean	2 lbs/plot Mean	California Mean	N. Caroline Mean	Florida Mean
T. urticae[2]	9.21	10.76	3.55 a	2.87 a	15.00 b
P. macropilis[1,2]	0.59**	0.40	0.24 a	0.71 b	0.11 a
Plant condition[1] (No. leaves/plant)	36.11**	22.79	36.69**	23.14	--

1. Means with double asterisks are significantly different from the means of the other ammonium nitrate level as well as from the other source of strawberry plant (P = 0.01) by t-test.

2. Values followed by the same letter are not different at 5% level by least significant difference.

Table 3. Influence of predator release ratio on strawberry plants and mite population density

Release ratio	Plant condition (No. leaves/plant) Mean[1]	*T. urticae* population density (No. individuals/leaf/week) Mean[1]	*P. macropilis* population density (No. individuals/leaf/week) Mean[1]
1:2	23.35 *	3.775	3.89
1:4	28.34	3.570	2.86
1:8	30.00	3.931	1.77
1:16	38.50	4.392	2.63
1:32	27.64	6.921	0.91
1:64	--	19.827	5.92
1:128	--	8.490	1.76
Check	21.44 *	2.270 *	--

1. Means followed by the same asterisk as the check are not significantly different (P = 0.05) according to Dunnett's test.

Table 4. Effect of nematicides on population densities of *Tetranychus urticae* and *Phytoseiulus macropilis*, and plant condition.

Nematicide	Conc. lbs ai/100 gal	Plant condition (No. leaves/plant)[1]	*T. urticae* population density (No. prey/leaf)[1]	*P. macropilis* population density (No. predators/leaf)[1]	Pest management value[2]
CGA-12223 10G	4	50.71 c	3.38 a	0.13 * a	13.22
Ethoprop 10G	10	25.23 b	5.83 b	0.13 * a	1.62
Carbofuran 10G	10	20.67 a	9.70 c	0.76 * a	0.40
Check		17.14 *	0.84 *	0.58 *	

1. Means followed by the same letter are not significantly different ($P = 0.05$) according to Duncan's multiple range test. Use of the asterisk (*) denotes that the means are not different from the check mean ($P = 0.05$) according to Dunnett's test.

2. Pest management value = (plant condition in treated plot - plant condition in check plot) x P
where P = (pest density in check plot (A) - pest density in treated plot (B)) + 1, when $A - B \geq 1$;
$P = 1$, when $1 \geq A - B \geq 0$,
or $P = 1/(B-A)$, when $A - B < 0$.

Table 5. Influence of predator release ratio and source of 'Tioga' strawberry plants on plant condition, twospotted spider mite infestation level and population density of predator, *P. macropilis*.

Release ratio	Plant condition (No. leaves/plant) Mean		Pest population (No. mites/leaf) Mean		Predator population (No. mites/leaf) Mean	
	California	N. Carolina	California	N. Carolina	California	N. Carolina
1:2 [2]	21.00 * a	17.69 a	2.99 a	4.36 b	0.06 a	0.74 a
1:4 [2]	32.29 b	25.38 a	1.26 a	7.93 b	0.11 a	0.47 a
1:8 [2]	36.07 a	40.93 b	3.05 a	3.97 a	0.07 a	0.28 a
1:16 [2]	46.00 b	15.57 a	2.27 a	12.62 b	0.07 a	0.45 a
1:32 [2]	40.00 b	15.29 a	6.18 * b	2.55 * a	0.10 a	0.08 a
1:64 [2]	--	--	18.93	--	0.59	--
1:128 [3]	--	--	--	8.05	--	0.18
Check [2]	19.00 * b	1.20 * a	4.89 * b	2.10 * a	--	--

1. Means followed by a single asterisk (*) are not significantly different from check mean ($P = 0.05$) according to Dunnett's test

2. Plant source means followed by the same letter at the same predator release ratio are not significantly different ($P = 0.05$) by t-test.

3. Plant source of this predator release ratio is from Florida.

Table 6. Influence of predator release ratio and nematicide on plant condition, twospotted spider mite infestation level.

Release ratio	Plant condition (No. leaves/plant) Mean				Spider mite population (No. mites/leaf) Mean			
	CGA-12223 (4 lbs ai/ 100 gal)	Ethoprop (10 lbs ai/ 100 gal)	Carbofuran (10 lbs ai/ 100 gal)	Check[3]	CGA-12223 (4 lbs ai/ 100 gal)	Ethoprop (10 lbs ai/ 100 gal)	Carbofuran (10 lbs ai/ 100 gal)	Check[3]
1:2[1,2]	31.56 b	21.28 a	27.00 b	13.50 *	4.11 a	4.59 b	4.42 ab	0.84 *
1:4[1,2]	50.71 c	34.00 b	13.86 * a	10.85 *	14.60 a	2.00 b	1.67 a	--
1:8[1,2]	55.00 c	34.42 * b	17.14 a	31.61 *	5.11 b	2.84 a	5.23 b	0.87 *
1:16[1,2]	57.57 c	20.29 * a	34.43 b	15.33 *	12.42 b	12.82 c	3.75 a	0.73 *
1:32[1,2]	58.71 b	16.14 * a	21.29 a	14.43 *	4.57 b	1.33 a	11.50 c	0.87 *
Check	--	--	--	0.71	--	--	--	0.49

1. Means followed by a single asterisk (*) are not significantly different from check mean (P = 0.05) according to Dunnett's test.

2. Chemical means followed by the same letter are not significantly different from the means of the other chemicals (P = 0.05) by Duncan's multiple range test.

3. Check means of 0.71 and 0.49 are significantly (P = 0.05) lower than the corresponding check means receiving the predators.

Table 7. Correlation coefficients among weekly population levels of *Tetranychus urticae*, *Phytoseiulus macropilis*, and plant conditions.

Response	No. of *P. macropilis* in past[1]				
	week 4	week 3	week 2	week 1	present week
No. *T. urticae* in past					
week 4	0.370 (0.0001)	0.265 (0.0006)	0.136 (0.0715)	-0.002 (0.9861)	-0.023 (0.7707)
week 3		0.366 (0.0001)	0.266 (0.0003)	0.132 (0.0625)	0.006 (0.9346)
week 2			0.368 (0.0001)	0.263 (0.0002)	0.137 (0.0415)
week 1				0.359 (0.0001)	0.240 (0.0002)
present week					0.426 (0.0001)
No. *P. macropilis* at					
week 4		0.354 (0.0001)	-0.028 (0.7150)	-0.013 (0.8651)	-0.002 (0.9792)
week 3			0.357 (0.0001)	-0.027 (0.7136)	0.005 (0.9420)
week 2				0.366 (0.0001)	-0.002 (0.9772)
week 1					0.367 (0.0001)
Plant condition					
No. leaves/plant	-0.192 (0.0254)	-0.155 (0.0714)	-0.120 (0.1688)	-0.109 (0.1759)	-0.043 (0.5796)

1. Values in the parenthesis are the type 1 error probabilities, that is, the probabilities of observing the recorded correlation if the variables are not correlated.

Table 6. Correlation coefficients and probabilities among responses of twospotted spider mite populations and plant condition.[1]

Response	No. of *T. urticae* in past				
	week 4	week 3	week 2	week 1	Present week
No. leaves/plant	-0.153 (0.0767)	-0.147 (0.0892)	-0.124 (0.1540)	-0.094 (0.2428)	-0.033 (0.6685)
No. *T. urticae* in past					
week 4		0.168 (0.0225)	-0.017 (0.8196)	0.242 (0.0022)	0.036 (0.6592)
week 3			0.170 (0.0143)	-0.031 (0.6755)	0.218 (0.0031)
week 2				0.168 (0.0114)	-0.015 (0.8125)
week 1					0.221 (0.0008)

1. Values in the parenthesis are the type 1 error probabilities, that is, the probabilities of observing the recorded correlation if the variables are not correlated.

Table 5. Regression coefficients and statistics of fit for ecological equilibrium point between predator and prey population of *P. macropilis* and *T. urticae*.

Predator-prey ratio	R-square and coefficients of parameter: Model A $\bar{r} = B_0 + B_1 \bar{\theta}$	Model B $\bar{r} = B_0 + B_1 \bar{\theta} + B_2 \bar{\theta}^2$	Model C $\bar{r} = B_0 + B_1 \bar{\theta} + B_2 \bar{\theta}^2 + B_3 \bar{\theta}^3$
1:2	$R^2 = 0.340$ ($P = 0.0002$) $\bar{r} = 9.360 - 4.161 \bar{\theta}$	$R^2 = 0.348$ ($P = 0.0012$) $\bar{r} = 8.023 - 0.548 \bar{\theta} + 2.222 \bar{\theta}^2$	$R^2 = 0.364$ ($P = 0.0024$) $\bar{r} = 2.860 + 20.211 \bar{\theta} - 27.852 \bar{\theta}^2 + 9.820 \bar{\theta}^3$
1:4	$R^2 = 0.0041$ ($P = 0.7110$) $\bar{r} = 5.501 + 0.406 \bar{\theta}$	$R^2 = 0.118$ ($P = 0.1252$) $\bar{r} = 3.319 + 8.044 \bar{\theta} - 5.111 \bar{\theta}^2$	$R^2 = 0.204$ ($P = 0.0587$) $\bar{r} = 1.082 + 23.932 \bar{\theta} - 30.486 \bar{\theta}^2 + 11.118 \bar{\theta}^3$
1:8	$R^2 = 0.298$ ($P = 0.0006$) $\bar{r} = 11.150 - 5.907 \bar{\theta}$	$R^2 = 0.645$ ($P = 0.0001$) $\bar{r} = 1.694 + 22.088 \bar{\theta} - 19.006 \bar{\theta}^2$	$R^2 = 0.689$ ($P = 0.0001$) $\bar{r} = -2.397 + 54.650 \bar{\theta} - 79.310 \bar{\theta}^2 + 32.023 \bar{\theta}^3$
1:16	$R^2 = 0.349$ ($P = 0.0001$) $\bar{r} = 12.610 - 6.273 \bar{\theta}$	$R^2 = 0.361$ ($P = 0.0009$) $\bar{r} = 10.053 + 0.582 \bar{\theta} - 4.186 \bar{\theta}^2$	$R^2 = 0.362$ ($P = 0.0025$) $\bar{r} = 8.326 + 8.174 \bar{\theta} - 14.199 \bar{\theta}^2 + 4.085 \bar{\theta}^3$
1:32	$R^2 = 0.547$ ($P = 0.0001$) $\bar{r} = 13.026 - 6.362 \bar{\theta}$	$R^2 = 0.571$ ($P = 0.0001$) $\bar{r} = 9.777 + 0.446 \bar{\theta} - 3.676 \bar{\theta}^2$	$R^2 = 0.577$ ($P = 0.0001$) $\bar{r} = -15.930 + 98.189 \bar{\theta} - 114.510 \bar{\theta}^2 + 37.700 \bar{\theta}^3$
1:64	$R^2 = 0.008$ ($P = 0.6063$) $\bar{r} = 9.775 - 1.454 \bar{\theta}$	$R^2 = 0.384$ ($P = 0.0006$) $\bar{r} = 29.494 - 56.535 \bar{\theta} + 32.139 \bar{\theta}^2$	$R^2 = 0.425$ ($P = 0.0007$) $\bar{r} = 44.565 - 124.723 \bar{\theta} + 122.205 \bar{\theta}^2 - 35.591 \bar{\theta}^3$
1:128	$R^2 = 0.365$ ($P = 0.0001$) $\bar{r} = 10.228 - 5.426 \bar{\theta}$	$R^2 = 0.690$ ($P = 0.0001$) $\bar{r} = -0.459 + 26.624 \bar{\theta} - 21.250 \bar{\theta}^2$	$R^2 = 0.801$ ($P = 0.0001$) $\bar{r} = -8.307 + 79.324 \bar{\theta} - 116.834 \bar{\theta}^2 + 49.986 \bar{\theta}^3$

Table 9. --continued.

Predator-prey ratio	R-square and coefficients of parameter Model D $\bar{r}^2 = B_0 + B_1\,\bar{\theta} + B_2\,\bar{\theta}^2$	 $\bar{r}^2 = B_0 + B_1\,\bar{\theta} + B_2\,\bar{\theta}^2 + B_3\,\bar{\theta}^3$
1:2	$R^2 = 0.299$ $(P = 0.0032)$ $\bar{r}^2 = 72.381 - 28.915\,\bar{\theta} - 14.410\,\bar{\theta}^2$	$R^2 = 0.322$ $(P = 0.0058)$ $\bar{r}^2 = -9.770 + 301.413\,\bar{\theta} - 422.254\,\bar{\theta}^2 + 156.266\,\bar{\theta}^3$
1:4	$R^2 = 0.118$ $(P = 0.1237)$ $\bar{r}^2 = 13.586 + 96.310\,\bar{\theta} - 67.237\,\bar{\theta}^2$	$R^2 = 0.236$ $(P = 0.0323)$ $\bar{r}^2 = -20.388 + 337.583\,\bar{\theta} - 452.578\,\bar{\theta}^2 + 168.841\,\bar{\theta}^3$
1:8	$R^2 = 0.536$ $(P = 0.0001)$ $\bar{r}^2 = 0.0004 + 245.833\,\bar{\theta} - 220.737\,\bar{\theta}^2$	$R^2 = 0.606$ $(P = 0.0001)$ $\bar{r}^2 = -70.103 + 803.839\,\bar{\theta} - 1264.437\,\bar{\theta}^2 + 548.768\,\bar{\theta}^3$
1:16	$R^2 = 0.328$ $(P = 0.0017)$ $\bar{r}^2 = 125.376 - 50.935\,\bar{\theta} - 27.726\,\bar{\theta}^2$	$R^2 = 0.333$ $(P = 0.0046)$ $\bar{r}^2 = 57.002 + 242.870\,\bar{\theta} - 415.210\,\bar{\theta}^2 + 156.076\,\bar{\theta}^3$
1:32	$R^2 = 0.435$ $(P = 0.0002)$ $\bar{r}^2 = 104.235 - 24.734\,\bar{\theta} - 27.772\,\bar{\theta}^2$	$R^2 = 0.581$ $(P = 0.0001)$ $\bar{r}^2 = -291.132 + 1478.550\,\bar{\theta} - 1732.403\,\bar{\theta}^2 + 579.827\,\bar{\theta}^3$
1:64	$R^2 = 0.308$ $(P = 0.0023)$ $\bar{r}^2 = 399.802 - 765.133\,\bar{\theta} + 419.480\,\bar{\theta}^2$	$R^2 = 0.339$ $(P = 0.0041)$ $\bar{r}^2 = 604.910 - 1693.090\,\bar{\theta} + 1645.185\,\bar{\theta}^2 - 484.356\,\bar{\theta}^3$
1:128	$R^2 = 0.638$ $(P = 0.0001)$ $\bar{r}^2 = -8.770 + 249.044\,\bar{\theta} - 214.128\,\bar{\theta}^2$	$R^2 = 0.752$ $(P = 0.0001)$ $\bar{r}^2 = -108.880 + 921.276\,\bar{\theta} - 1433.407\,\bar{\theta}^2 + 637.624\,\bar{\theta}^3$

$\bar{\theta}$ = Arc tan (PN_1/TN_2), $\bar{r} = \sqrt{(PN_1)^2 + (TN_2)^2}$, where PN_1 is (No. of predators at week t * 10) + 1, TN_2 is (No. of preys at week t + 1 * 100) + 1.

Table 10. Development of resistance of twospotted spider mite, Tetranychus urticae, to dicofol (1.6 EC) selection pressure.

Generation (week)	LC_{50} (PPM)	Increased resistance (PPM)	Fiducial limit (PPM)	% increase of resistance (by one generation)	% cumulated increase of resistance	LC_{40} (Log PPM)	LC_{60} (Log PPM)
0	238.8	--	111.7 - 510.4	--	--	2.265	2.491
1	382.8	144.0	267.6 - 547.7	60.3	60.3	2.489	2.635
2	430.5	47.7	330.7 - 560.6	12.5	80.3	2.488	2.779
3	468.8	38.3	341.6 - 643.0	8.9	96.3	2.524	2.817
4	440.1	-28.7	316.3 - 613.9	-6.1	84.3	2.399	2.889
5	494.2	54.1	479.4 - 509.4	12.3	106.9	2.660	2.728
6	521.3	27.1	503.7 - 559.4	5.5	118.3	2.678	2.761
7	572.9	51.6	555.3 - 591.0	9.9	139.9	2.717	2.799

Table 11. Development of resistence of twospotted spider mite, Tetranychus urticae, to naled (8 EC) selection pressure.

Generation (week)	LC_{50} (PPM)	Increased resistence (PPM)	Fiducial limit (PPM)	% Increase of resistence (by one generation)	% cumulated increases of resistence	LC_{40} (Log PPM)	LC_{60} (Log PPM)
0	458.8	--	406.5 - 518.7	--	--	2.609	2.714
1	597.0	138.8	356.9 - 999.7	30.1	30.1	2.588	2.965
2	633.4	36.3	407.4 - 986.3	6.1	38.2	2.607	2.895
3	652.9	19.5	331.9 - 1285.3	3.1	42.3	2.627	3.103
4	598.4	-54.5	567.7 - 630.8	-8.4	30.4	2.617	2.937
5	590.2	-8.2	213.8 - 1770.1	-1.4	28.7	2.540	3.001
6	519.7	-70.5	502.4 - 537.5	-12.0	13.3	2.651	2.701
7	633.1	113.4	612.9 - 654.0	21.8	38.0	2.762	2.841

Table 12 Effect of acaricides on spider mite population density on Florida grown 'Tioga' strawberries.

Material[1]	lb ai/acre	Average no. mites/leaf on: Jan 24	Jan 31	Feb 8	Feb 22	Mar 8	Seasonal average[2]
Dicofol 35 WP	1.0	54	97	59	17	88	63 * b
Naled 8 EC	1.0	77	68	47	11	40	53 * b
Omite 30 WP	0.5	67	60	11	11	5	30 a
Dicofol 1.6EC	1.0	72	54	4	9	4	29 a
Dicofol 1.6 EC + Naled 8 EC	0.5 0.5	34	86	24	26	27	39 a
Dicofol 35 WP + Omite 30 WP	0.5 0.25	28	75	8	11	4	25 a
Naled 8 EC + Omite 30 WP	0.5 0.25	56	65	10	8	13	30 a
Dicofol 1.6 EC + Naled 8 EC + Omite30 WP	0.3 0.3 0.18	106	57	13	6	20	40 a
Check		136	103	87	27	92	89 *

1. Materials were applied on January 22, 29, February 6, 20, 26, and March 6.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test and means followed by a single asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

Table 13. Effect of acaricides on spider mite population density on 'Tioga' strawberries one day after spray.

Material			lb ai/acre	Average no. mites/leaf[2] egg		active		total		Corrected percentage mortality[2,3]	
Dicofol	35	WP	1.0	36 *	a	79	d	115	e	-6	ab
Naled	8	EC	1.0	71 *	a	82	de	153	g	17	h
Omite	30	WP	0.5	53 *	a	89	e	142	f	-4	bcd
Dicofol	1.6	EC	1.0	44 *	a	45	cb	89	d	12	fg
Dicofol + Naled	1.6 8	EC EC	0.5 0.5	44 *	a	98	f	142	f	13	gh
Dicofol + Omite	35 30	WP WP	0.5 0.25	24 *	a	39	c	63	b	-2	de
Naled + Omite	8 30	EC WP	0.5 0.25	22 *	e	50	b	72	c	-5	bc
Dicofol + Naled + Omite	1.6 8 30	EC EC WP	0.3 0.3 0.18	32 *	a	88	e	121	e	-10	a
Vendex	50	WP	0.5	18 *	a	28	a	47	a	0	e
Vendex	50	WP	0.25	49 *	a	29	a	78	c	8	f
Check				156 *		198 *		356 *			

1. Materials were applied on January 29

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by an asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment.

Table 14 Effect of acaricides on spider mite population density on 'Tioga' strawberries two days after spray.

Material[1]			lb ai/ acre	Average no. mites/leaf[2] egg		active		total		Corrected percentage mortality[2,3]	
Dicofol	35	WP	1.0	70 *	b	30	ab	100	d	-7	c
Naled	8	EC	1.0	35 *	ab	42 *	ab	77	cd	17	a
Omite	30	WP	0.5	38 *	ab	63 *	b	101	d	-14	d
Dicofol	1.6	EC	1.0	4	a	23	a	28	a	15	a
Dicofol + naled	1.6 8	EC EC	0.5 0.5	34 *	ab	30	ab	64	abc	8	b
Dicofol + Omite	35 30	WP WP	0.5 0.25	14 *	a	18	a	32	ab	-7	c
Naled + Omite	8 30	EC WP	0.5 0.25	22 *	ab	30	ab	52	abc	-14	d
Dicofol + Naled + Omite	1.6 8 30	EC EC WP	0.3 0.3 0.18	12 *	a	29	ab	40	abc	-14	d
Vendex	50	WP	0.5	6	a	17	a	23	a	-13	d
Vendex	50	WP	0.25	25 *	ab	20	a	45	abc	-3	c
Check				61 *		71 *		132 *			

1 Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by an asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment.

Table 15. Effect of Acaricides on spider mite population density on 'Tioga' strawberries three day after spray.

Material[1]	lb ai/ acre	Average no. mites/leaf[2] Egg		Active		Total		Corrected percentage mortality[2,3]	
Olcofol 35 WP	1.0	41	h	42	f	80 *	a	11	c
Naled 8 EC	1.0	44	i	35	e	79 *	a	11	c
Omite 30 WP	0.5	15	e	15	d	29	c	19	b
Olcofol 1.6EC	1.0	10	b	10	c	20	b	30	a
Olcofol 1.6EC + Naled 8 EC	0.5 0.5	19	g	16	d	35	c	26	a
Olcofol 35 WP + Omite 30 WP	0.5 0.25	10	b	8	c	19	b	-7	e
Naled 8 EC + Omite 30 WP	0.5 0.25	12	d	9	c	21	b	16	b
Olcofol 1.6EC + Naled 8 EC + Omite 30 WP	0.3 0.3 0.18	17	f	42	f	58	d	-21	f
Vendex 50 WP	0.5	9	b	2	a	11	a	0	d
Vendex 50 WP	0.25	4	a	5	b	9	a	3	d
Check		28 *		52 *		80 *			

1. Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by an asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, C_b is no. mites/leaf in check plots before treatment.

Table 16. Effect of acaricides on spider mite population density on 'Tioga' strawberries five days after spray.

Material[1]		lb ai/acre	Average no. mites/leaf[2] Egg		Active		Total		Corrected percentage recovery[2,3]		Corrected percentage mortality[2,4]	
Dicofol	35WP	1.0	33	f	40	e	73	f	13	c	-2	cd
Naled	8EC	1.0	39	g	18	d	57	e	-3	a	0	c
Omite	30WP	0.5	21	e	15	c	36	c	46	d	8	b
Dicofol	1.6EC	1.0	9 *	bc	9	a	17	a	14	c	17	a
Dicofol + Naled	1.6EC 8EC	0.5 0.5	13	d	16	cd	29	b	7	b	16	a
Dicofol + Omite	35WP 30WP	0.5 0.25	5	a	11	b	17	a	13	c	7	b
Naled + Omite	8EC 30WP	0.5 0.25	13	d	15	c	28	b	58	e	-5	d
Dicofol + Naled + Omite	1.6EC 8EC 30WP	0.3 0.3 0.18	10 *	c	39	e	49 *	d	75	f	-8	d
Vendex	50WP	0.5	7	b	9	a	16	a	73	f	1	c
Vendex	50WP	0.25	10 *	c	8	a	18	a	114	g	13	a
Check			10 *		36 *		45 *					

1. Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by an asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage recovery = $\frac{X_a - X_b}{X_b} \times \frac{C_5}{C_3} \times 100$

where X_a is no. mites/leaf at day 5, X_b is no. mites/leaf at day 3, C_5 is no. mites/leaf from the check plots at day 5, and C_3 is no. mites/leaf from the check plots at day 3.

Table 16. - continued

4. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment.

Table 17. Effect of acaricides on spider mite population density on 'Tioga' strawberries six days after treatment.

Material[1]	lb ai/acre	Average no. mites/leaf[2] egg		active		total		Corrected percentage recovery[2,3]		Corrected percentage mortality[2,4]	
Dicofol 35 WP	1.0	65	g	35	c	100	g	29	c	-7	de
Naled 8 EC	1.0	42	f	37	cd	79	f	8	b	-4	cde
Omite 30 WP	0.5	23	d	28	b	52	e	82	f	6	ab
Dicofol 1.6EC	1.0	11	b	20	a	31	b	67	e	12	a
Dicofol 1.6EC + Naled 8 EC	0.5 0.5	19 *	c	35	c	54	e	59	e	10	a
Dicofol 35WP + Omite 30WP	0.5 0.25	6	a	18	a	24	a	34	d	4	abc
Naled 8 EC + Omite 30 WP	0.5 0.25	19 *	c	28	b	47	d	128	g	-22	f
Dicofol 1.6 EC + Naled 8 EC + Omite 30 WP	0.3 0.3 0.18	12	b	39	d	51	e	-5	a	-2	bcd
Vendex 50 WP	0.5	17 *	c	20	a	36	c	240	h	-30	f
Vendex 50 WP	0.25	31	e	21	a	51	e	444	i	-14	e
Check		18 *		50 *		69 *					

1. Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by an asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage recovery = $\dfrac{X_a - X_b}{X_b} \times \dfrac{C_6}{C_3} \times 100$

where X_a is no. mites/leaf at day 6, X_b is no. mites/leaf at day 3, C_6 is no. mites/leaf from the check plots at day 6, and C_3 is no. mites/leaf from the check plots at day 3.

4. Corrected percentage mortality = $\dfrac{T_b - T_a}{T_b} \times \dfrac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment.

Table 18. Effect of acaricides on spider mite population density on 'Tioga' strawberries eight days after treatment.

Material[1]	lb ai/acre	Average no. mites/leaf[2] egg		active		total		Corrected percentage recovery[2,3]		Corrected percentage mortality[2,4]	
Dicofol 35 WP	1.0	52	f	31	d	83 *	c	-5	b	6	c
Naled 8 EC	1.0	36	a	54	f	90	c	9	c	-5	d
Omite 30 WP	0.5	19 *	ab	21	bc	40	a	29	d	18	a
Dicofol 1.6 EC	1.0	25 *	c	11	a	36	a	75	f	13	b
Dicofol 1.6 EC + Naled 8 EC	0.5 0.5	23 *	bc	38	e	61	b	64	e	11	b
Dicofol 35 WP + Omite 30 WP	0.5 0.25	19 *	a	19	b	38	a	91	g	-10	e
Naled 8 EC + Omite 30 WP	0.5 0.25	31	d	26	cd	57	b	158	h	-29	f
Dicofol 1.6 EC + Naled 8 EC + Omite 30 WP	0.3 0.3 0.18	29	d	28	d	58	b	-7	b	-2	d
Vendex 50 WP	0.5	20 *	ab	18	b	38	a	235	i	-27	f
Vendex 50 WP	0.25	39	e	17	b	55	b	-53	a	-11	e
Check		22 *		64 *		86 *					

1 Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by the asterisk (*) are not significantly different from check mean (P = 0.05) by Dunnett's test.

3. Corrected percentage recovery = $\frac{X_a - X_b}{X_b} \times \frac{C_8}{C_3} \times 100$

where X_a is no. mites/leaf at day 8, X_b is no. mites/leaf at day 3, C_8 is no. mites/leaf from the check plots at day 8, and C_3 is no. mites/leaf from the check plots at day 3.

4. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment.

Table 15. Effect of acaricides on daily spider mite population density on 'Tioga' strawberries.

Material[1]	lb ai/acre	Average no. mites/leaf/day [2,3]	Corrected percentage mortality [2,4]
Dicofol 35 WP	1.0	209 * cd	7 cd
Naled 8 EC	1.0	177 * cd	-6 fg
Omite 30 WP	0.5	122 * bcd	21 b
Dicofol 1.6EC	1.0	18 a	51 a
Dicofol 1.6EC + Naled 8 EC	0.5 0.5	119 * bcd	13 c
Dicofol 35 WP + Omite 30 WP	0.5 0.25	61 ab	6 de
Naled 8 EC + Omite 30 WP	0.5 0.25	92 abc	-11 g
Dicofol 1.6EC + Naled 8 EC + Omite 30 WP	0.3 0.3 0.18	125 * bcd	-1 ef
Vendex 50 WP	0.5	82 abc	8 cd
Vendex 50 WP	0.25	57 ab	1 ef
Check		223 *	

1. Materials were applied on January 29.

2. Chemical means followed by the same letter are not significantly different from other chemical means at 5% level by Duncan's multiple range test, and means followed by the asterisk (*) are not significantly different from check mean ($P = 0.05$) by Dunnett's test.

3. Average no. mites per leaf per day = $\bar{X} \times \bar{C}_a/C_b$
where $\bar{X}$ is average no. of mites per leaf per day on treated plot, $\bar{C}a$ is average no. of mites per leaf per day from check plots after treatment, and C_b is no. of mites per leaf from check plots before treatment.

4. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$
where T_a is no. of mites per leaf after treatment, T_b is no. of mites per leaf before treatment, C_a is no. of mites per leaf in check plots after treatment, and C_b is no. of mites per leaf in check plots before treatment.

Table 29 Comparison of actual and hypothetical effect of acaricides on spider mite population density on 'Tioga' strawberries

Material[1]		lbs ai/ acre	Average no. mites/leaf/ day Actual[2]	Average no. mites/leaf/ day Hypothetical	Corrected percentage mortality[3] Actual[2]	Corrected percentage mortality[3] Hypothetical
Dicofol	(A)	1.0	205 f		7 cd	
Naled	(B)	1.0	177 e		-6 ef	
Omite	(C)	0.5	122 d		21 b	
Dicofol	(D)	1.0	18 e		51 e	
Dicofol + Naled		0.5	119 d	97 (D + B)/2	13 c	23 (D + B)/2
Dicofol[4] + Omite		0.5 0.25	61 b	165 ** (A + C)/2	6 d	14 (A + C)/2
Naled[4] + Omite		0.5 0.25	92 c	149 ** (B + C)/2	-11 f	8 * (B + C)/2
Dicofol[4] + Naled + Omite		0.3 0.3 0.18	125 d	99 (D + B + C)/3	-1 e	25 ** (D + B + C)/3

1. Materials were applied on January 29.

2. Means followed by the same letter are not significantly different at 5% level by Duncan's multiple range test.

3. Corrected percentage mortality = $\frac{T_b - T_a}{T_b} \times \frac{C_a}{C_b} \times 100$

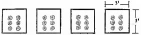
where T_a is no. mites/leaf after treatment, T_b is no. mites/leaf before treatment, C_a is no. mites/leaf in check plots after treatment, and C_b is no. mites/leaf in check plots before treatment

4. Values with a single or double asterisks are significantly different from the corresponding values at 1% or 5% level, respectively, by t-test.

Figure 1. The experimental design and field block arrangement for population study of twospotted spider mite and its predator, *P. macropilis* on 'Tioga' strawberry plants. a. Experiment 1A. b. Experiment 1B

a. Experiment IA.

Plant source	California (100)	N. Carolina (200)	California	N. Carolina
Ammonium nitrate.	4 lbs/plot (20)	2 lbs/plot (10)	4 lbs/plot	2 lbs/plot
Nemati-cide	Carbofuran (4)	CGA-12223 (2)	Ethoprop (3)	Check (1)



b. Experiment IB.

Plant source:	California (100)	California (100)	Florida (300)	N. Caroline (200)
Ammonium nitrate:	4 lbs/plot (20)	2 lbs/plot (10)	4 lbs/plot	2 lbs/plot

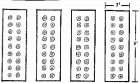
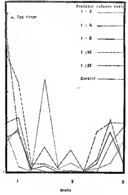
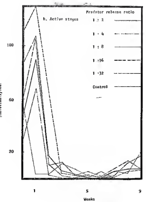


Figure 2. Effects of predator (<u>Phytoseiulus macropilis</u>) release ratio on population density of <u>Tetranychus urticae</u>: a. egg stage, b. active stages, and c. all stages.



Predator release ratio
a. Egg stage
1 : 2
1 : 4
1 : 8
1 :16
1 :32
Control
100
60
20
Individuals/leaf
1
5
9
Weeks



b. Active stages
Predator release ratio
1 : 2
1 : 4
1 : 8
1 : 16
1 : 32
Control
100
60
20
Individuals/leaf
1
5
9
Weeks

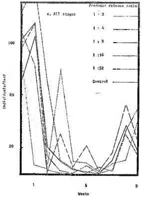
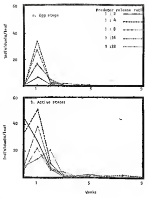
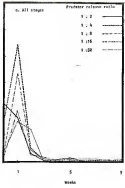

Predator release ratio
c. All stages
1 : 2
1 : 4
1 : 8
1 :16
1 :32
Control
100
60
20
Individuals/leaf
1
5
9
Weeks

Figure 3. Effects of predator (P. macropilis) release ratio on predator population density a. egg stage, b. active stages, c. all stages.



Predator release rati
1 : 2
1 : 4
1 : 8
1 : 16
1 : 32
a. Egg stage
b. Active stages
Individuals/leaf
60
40
20
1
5
9
Weeks



c. All stages
Predator release ratio
1 : 2
1 : 4
1 : 8
1 :16
1 :32
80
40
0
Individuals/leaf
1
5
9
Weeks

Figure 4. Responses of predator-prey ratio of _Phytoseiulus macropilis_ and _Tetranychus urticae_ to predator release ratio.

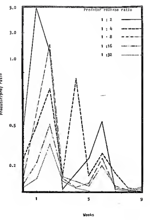
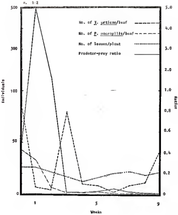
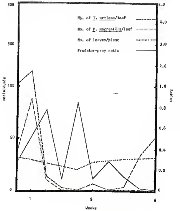

Predator release ratio
1 : 2
1 : 4
1 : 8
1 :16
1 :32
5.0
3.0
1.0
0.5
0.2
Predator/prey ratio
1
5
9
Weeks

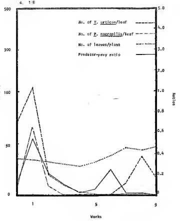
Figure 5. Effects of predator release ratio on population densities of twospotted spider mite, _T. urticae_, and its predator, _P. macropilis_, strawberry plant condition, and predator-prey ratio a. 1:2, b. 1:4, c. 1:8, d. 1:16, e. 1:32, f. control.



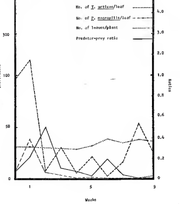
#. 1 2
500
300
100
50
0
5.0
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.2
0
No. of T. urticae/leaf
No. of P. macropilis/leaf
No. of leaves/plant
Predator-prey ratio
Individuals
Ratios
1
5
9
Weeks

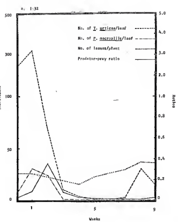
b. 1:4


500
300
100
50
0
Individuals
5.0
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.2
0
Ratios
1
5
9
Weeks
No. of T. urticae/leaf
No. of P. macropilis/leaf
No. of leaves/plant
Predator-prey ratio

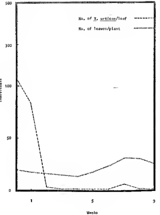

c. 1 B
No. of T. urticae/leaf
No. of P. macropilis/leaf
No. of leaves/plant
Predator-prey ratio
Individuals
Ratios
Weeks
500
300
100
50
0
5.0
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.2
0
1
5
9

d. 1:16


No. of T. urticae/leaf
No. of P. macropilis/leaf
No. of leaves/plant
Predator-prey ratio
500
300
100
50
0
Individuals
5.0
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.2
0
Ratios
1
5
9
Weeks


a. 1-32
No. of T. urticae/leaf
No. of P. macropilis/leaf
No. of leaves/plant
Predator-prey ratio
Individuals
Ratios
Weeks
500
300
100
50
0
5.0
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.2
0
1
5
9

f. Control



No. of T. urticae/leaf
No. of leaves/plant
500
300
100
50
0
Individuals
1
5
9
Weeks

Figure 6. Responses of strawberry plant condition (number of leaves per plant) to predator release ratio.

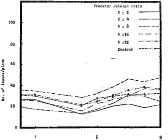
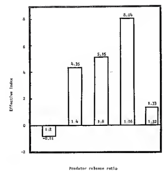

Predator release ratio
1 : 2
1 : 4
1 : 8
1 :16
1 :32
Control
100
80
60
40
20
0
No. of leaves/plant
1
5
9
Weeks

Figure 7 Effects of initial predator release ratio on the index of plant condition and spider mite density.ł

ł- Index – (Seasonal average number of leaves per plant on predator introduced plot – seasonal average number of leaves on control plot)/(weekly average of spider mite on predator introduced plot – weekly average number of spider mites on control plot)


8.04
5.15
4.35
1.33
1:4
1:8
1:16
1:32
1:2
-0.81
8
6
4
2
0
-2
Effective Index
Predator release ratio

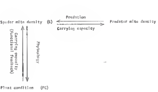
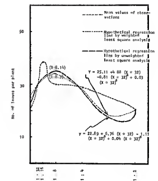


Figure 8. A simplified hypothetical causal network among predator, prey or pest, and host plant condition.

Figure 9. Real and predicted response of average seasonal plant condition to the initial predator-prey ratio at release.



Mean values of observations
Hypothetical regression line by weighted least square analysis
Hypothetical regression line by unweighted least square analysis
(1:8.14)
(1:8.3)
Y = 25.11 + 4.88 (X ÷ 32) − 0.81 (X ÷ 32)² + 0.03 (X ÷ 32)³
Y = 22.89 + 6.76 (X ÷ 32) − 1.11 (X ÷ 32)² + 0.04 (X ÷ 32)³
50
30
10
No. of leaves per plant
1:32
1:16
1:8
1:4
1:2
Predator-prey ratio

Figure 10. Response of prey population density to initial predator-prey ratio at release, with Phytoseiulus macropilis and Tetranychus urticae being the predator and prey, respectively.

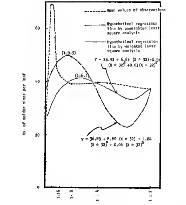
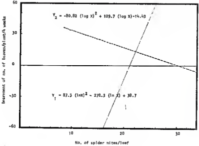

Mean values of observations
Hypothetical regression line by unweighted least square analysis
Hypothetical regression line by weighted least square analysis
(1:9.5)
(1:6.1)
Y = 25.93 + 6.83 (X * 32)-0.9
(X * 32)^2 +0.03(X * 32)^3
y = 36.89 + 8.60 (X * 32) - 1.64
(X * 32)^2 + 0.06 (X * 32)^3
60
40
20
0
No. of spider mites per leaf
1:16
1:8
1:4
1:2
Predator-prey ratio

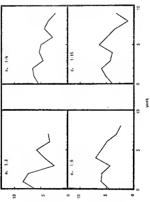
Figure 11 Hypothetical regression line of improving and declining plant condition per four weeks by spider mite density.

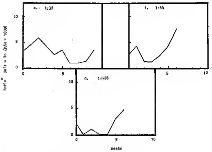


Y_1 : No. of leaves lost per plant per 4 weeks.

Y_2 : No. of leaves gained per plant per 4 weeks.

Figure 12. Weekly ratio between predator and prey population to different release ratios: a. 1:2, b. 1:4, c. 1:8, d. 1:16, e. 1:32, f. 1:64, g. 1:128.


a. 1:2
b. 1:4
c. 1:8
d. 1:16
10
5
0
Week
Ratio*



* Ratio is calculated as: ln ((No. of predators per leaf/no. of prey per leaf) ×1000).

Figure 13. Depiction of the phase space of population of P. macropilis at week t and its prey, T. urticae at week t + 1.

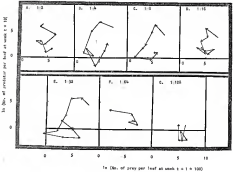

A. 1:2
B. 1:4
C. 1:8
D. 1:16
E. 1:32
F. 1:64
G. 1:128
ln (No. of predator per leaf at week t * 10)
ln (No. of prey per leaf at week t + 1 * 100)
0
5
10

Figure 14: Graphical illustration of the translocation of origin of coordinate to gravity center of the observed set points in an initial predator-prey ratio.

r _ the length of a line (r_1) from any point (P) on the trajectory to the origin of coordinate (0 (0, 0)), it can be calculated from the formula of

$$r = \sqrt{TN_{t+1}^2 + PN_t^2}$$

r_0 : the length of the line (r_2) from new center of spiral ($\bar{0}$ (TN_i, PN_{i-1})) to the origin of coordinate, it is calculated by the formula of

$$\sqrt{TN_i^2 + PN_{i-1}^2} .$$

θ : angle between abscissa of horizontal axis (TN_{t+1}) and r_1. It can be obtained by formula

$$\theta = \mathrm{Tan}^{-1} (PN_t / TN_{t+1}).$$

θ_0 : angle between horizontal axis and r_2. It can be obtained by the formula

$$\theta_0 = \mathrm{Tan}^{-1} (PN_{i-1} / TN_i).$$

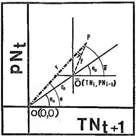

PNt
P
r
r̄
θ_0
$\bar{\theta}$
r_0
Ō(TNi, PNi-1)
θ_0
θ
o(0,0)
TNt+1

Figure 15. Corrected percentage changes of twospotted spider mite populations to acaricides. (A) Dicofol (35 WP, 1.0). (B) Naled (8 EC, 1.0). (C) Omite (30 WP, 0.5). (D) Dicofol (1.6 EC, 0.5). (E) Dicofol (35 WP, 0.5) + Omite (30 WP, 0.25). (F) Naled (8 EC, 0.5) + Omite (30 WP, 0.25). (G) Dicofol (1.6 EC, 0.3) + Naled (8 EC, 0.3) + Omite (30 WP, 0.18). (H) Vendex (50 WP, 0.25). (I) Vendex (50 WP, 0.5). (J) Dicofol (1.6 EC, 1.0)[1]

1. Unit of the second value in each parenthesis is pound of active ingredient per acre.

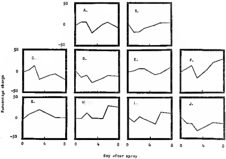
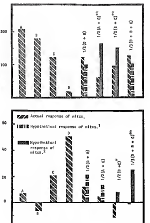

A.
B.
C.
D.
E.
F.
G.
H.
I.
J.
50
0
-50
Percentage change
0
4
8
Day after spray

Figure 16. Comparison between actual and hypothetical responses of twospotted spider mite population densities to (A). dicofol (35 WP, 1 lb ai/acre), (B). naled (8 EC, 1 lb ai/acre), (C). omite (30 WP, 0.5 lb ai/acre), (D). dicofol (1.6 EC, 1 lb ai/acre), and their combinations.

1. Not significantly different from actual response of mites.

2. Significantly different from actual response of mites at 5% level (*) or 1% level (**).



No. of individuals/leaf/day
200
100
A
B
C
D
1/2(B + B)
1/2(A + C)**
1/2(B + C)**
1/3(B + B + C)
Actual response of mites.
Hypothetical response of mites.1
Hypothetical response of mites.2
Corrected percentage mortality
60
40
20
0
-20
A
B
C
D
1/2(B + B)
1/2(A + C)
1/2(B + C)*
1/3(B + B + C)**

Acaricides

Appendix 1a. Populations of _Tetranychus urticae_ and its predator, _Phytoseiulus macropilis_, with one-week difference.

Week after predator release (t)	Predator-prey ratio 1:2		1:4		1:8		1:16		1:32		1:64		1:128	
	PN_t*	TN_{t+1}**	PN_t	TN_{t+1}	PN_t	TN_{t+1}	PN_t	TN_{t+1}	PN_t	TN_{t+1}	PN_t	TN_{t+1}	PN_t	TN_{t+1}
0	[illegible]	[illegible]	5.82	7.31	[illegible]	7.11	4.09	7.23	[illegible]	[illegible]	1.77	6.39	0.97	[illegible]
1	5.80	3.69	6.79	4.91	6.50	5.30	5.81	4.85	5.72	6.53	1.61	6.93	-2.30	5.79
2	4.21	6.68	4.91	3.22	4.58	4.63	4.17	5.36	5.50	4.55	1.39	5.54	-0.19	5.48
3	2.30	4.50	0.91	1.87	2.30	3.40	3.40	4.00	2.08	3.61	0.92	7.38	-2.30	6.57
4	2.55	3.99	0.41	3.71	1.61	2.94	1.19	4.98	-0.69	2.01	3.11	6.16	-2.30	5.03
5	3.12	2.95	1.72	2.27	0.10	1.45	2.38	3.23	-1.20	-0.69	3.61	1.84	1.19	5.08
6	2.96	3.77	-1.61	4.05	-0.19	4.77	1.38	5.09	-1.80	3.35	2.62		3.00	
7	0.59	4.70	1.61	5.83	1.16	5.93	1.87	6.67	-2.30	6.68				
8	1.61	6.06	2.62	5.25	1.61	5.05	0.92	5.47	0.10	4.92				
9		4.70	1.61				2.01	4.27	1.61	3.16				

* PN_t = ln (No. of predators at week t x 10)

** TN_{t+1} = ln (No. of spider mites at week (t+1) x 100)

Appendix 16. Weekly prey-predator ratio of *Tetranychus urticae* and *Phytoseiulus macropilis*

Week after predator release (t)	Predator-prey ratio						
	1:2	1:4	1:8	1:16	1:32	1:64	1:128
0	6.21	5.52	4.83	4.14	3.43	2.71	2.08
1	8.45	6.38	6.30	5.36	4.55	4.43	0.00
2	7.43	6.63	6.19	6.23	5.88	1.39	1.10
3	2.56	4.61	4.58	4.45	4.43	1.39	0.00
4	4.95	5.46	7.42	4.11	2.64	2.64	0.00
5	5.97	5.05	6.37	6.60	3.61	4.37	3.09
6	3.40	2.89	5.26	5.06	1.10	7.69	4.83
7	3.69	4.47	3.30	3.69	1.10		
8		3.69	2.56	1.10	1.39		
9		2.30		3.47	3.61		

Appendix 2. Main effects and cross products of spider mite population per leaf on Tioga strawberry.

Variable	Week after predator release [1, 2]							
	1	4	5	6	[illegible]	8	9	Seasonal total
Release ratio	3.2317 (0.0407)*	2.0943 (0.1311)	0.3802 (0.5333)	1.0851 (0.4138)	1.7223 (0.1985)	1.0255 (0.4433)	0.8167 (0.5598)	5.9539** (0.0001)
Nitrogen	0.0005 (0.9824)	12.6727 (0.0035)**	1.0358 (0.3164)	0.8483 (0.3738)	0.0101 (0.9215)	2.5655 (0.1332)	0.0233 (0.8810)	3.1595* (0.0459)
Source								11.6807 (0.0008)**
Nematicide	2.7192 (0.1020)	4.8730 (0.0258)	3.7324 (0.0514)	2.2913 (0.1393)	1.7173 (0.2170)	4.2365 (0.0376)*	2.5056 (0.1130)	12.7139** (0.0005)
Release ratio x nitrogen								4.0123 (0.0024)**
Release ratio x plant source								7.1817 (0.0001)**
Release ratio x nematicide								2.3232 (0.0591)

Appendix 3. Main effects and cross products of P. macropilis population per leaf on Tioga strawberry.

Variable	Week after predator release [1, 2]							
	3	4	5	6	7	8	9	Seasonal total
Release ratio	1.6630 (0.2123)	0.8456 (0.5423)	1.0254 (0.4433)	0.9508 (0.5175)	1.1188 (0.3980)	1.0352 (0.4383)	0.0667 (0.5298)	1.0643 (0.3001)
Nitrogen	0.2345 (0.6363)	1.7468 (0.2091)	1.9101 (0.1902)	1.0281 (0.3231)	4.4384 (0.0551)*	1.6079 (0.2270)	2.2118 (0.1608)	0.3375 (0.5623)
Source								0.0928 (0.7611)
Nematicide	0.3099 (0.7423)	4.2479 (0.0373)*	4.3284 (0.0355)*	1.8995 (0.1879)	9.6549 (0.0030)**	2.9758 (0.0852)	6.1663 (0.0130)*	0.3537 (0.5531)
Release ratio x nitrogen								5.5749 (0.0002)**
Release ratio x plant source								0.9219 (0.5450)
Release ratio x nematicide								4.8551 (0.0019)**

Appendix 4. Main effects and cross products of number of leaves per strawberry plant.

Variable	Week after predator release [1, 2]							
	3	4	5	6	7	8	9	Seasonal total
Release ratio	0.3947 (0.8442)	1.1602 (0.3794)	0.6422 (0.6738)	0.4900 (0.7793)	0.8560 (0.5361)	0.8330 (0.5499)	0.8981 (0.5116)	12.9751 (0.0001)**
Nitrogen	0.0363 (0.8519)	4.3317 (0.0577)	2.4908 (0.1385)	2.8813 (0.1134)	5.9868 (0.0294)	4.0874 (0.0643)	3.1669 (0.0985)	10.0053 (0.0019)**
Source								0.9080 (0.3421)
Nematicide	3.1836 (0.0736)	1.6972 (0.2205)	3.5054 (0.0596)	3.6191 (0.0553)	7.8374 (0.0061)**	7.9092 (0.0059)**	9.2417 (0.0035)**	26.2989 (0.0001)**
Release ratio x nitrogen								9.5882 (0.0001)**
Release ratio x plant source								8.0053 (0.0001)**
Release ratio x nematicide								8.4182 (0.0001)**

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Chen-ing Thomas Shih was born on January 10, 1943, in Shanghai, China. After graduation from Chien-Shou High School, he attended National Chung-Hsing University as an entomology major and graduated with the degree Bachelor of Science in June, 1967. From July, 1967 through July 1968 he served as a Second Lieutenant in Chinese Army. He then returned to his alma mater to teach and conduct research as an assistant in Department of Entomology and as a part-time assistant in Agriculture Extension Department of the University in which he was in charge of pest management. In September, 1972 he was awarded a two-year fellowship from National Science Council, Republic of China, and enrolled at graduate school of the University of Florida. He majored in entomology and graduated in August 1974 with degree of Master of Science. He then was awarded a research assistantship from the Department to study for his doctoral degree.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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